VOLUME 86 NO. IR3
SEPTEMBER 1960
PART 1

JOURNAL of the

Irrigation and Drainage Division

PROCEEDINGS OF THE

AMERICAN SOCIETY OF CIVIL ENGINEERS

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The index for 1959 was published as ASCE Publication 1960-10 (list price $2.00); indexes for previous years are also available.

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Journal of the

IRRIGATION AND DRAINAGE DIVISION

Proceedings of the American Society of Civil Engineers

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September, 1960

Papers

(over)

DISCUSSION

Journal of the
IRRIGATION AND DRAINAGE DIVISION
Proceedings of the American Society of Civil Engineers

DEVELOPMENT OF ROTATIONAL IRRIGATION IN TAIWAN

Lee Chow,[1] F. ASCE

SYNOPSIS

Rotational irrigation, now rapidly replacing the old irrigation practice in Taiwan, is described with special emphasis on design and operation of such irrigation systems. Some background information on rotational irrigation experimentation and demonstration is given. Future improvements to be made and possible research to be done are also pointed out.

EARLY CONTINUOUS IRRIGATION PRACTICE

The irrigation history in Taiwan dates back to Yuan Dynasty (1277-1367) in Chinese history. People built canals to irrigate the land they cultivated. The population and the farm land than were both scarce. There was no need to limit the use of irrigation water. That was the origin of the old continuous irrigation practice.

Rice plantations are the most common in Taiwan. Wherever irrigation water is adequate, two rice crops are grown in a year. Before rice transplanting, the field is soaked with water. For sandy soil the soaking may be eliminated. After soaking, levelling of the ground will be done in preparation for transplanting. During the early growing season, there are two or three times each for weeding and application of fertilizer. The growing period of the rice crop is about

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120 days and that of second crop is a little shorter. Excluding the time of weeding and fertilizer application and a short period before harvesting when no water is applied, irrigation continues for about 90 to 100 days.

FIRST EXPERIMENTS ON ROTATIONAL IRRIGATION

While with the Joint Commission On Rural Reconstruction (JCRR), the author was surprised at the low duty of irrigation water in Taiwan, which averaged about 400 hectares of paddy field per cu m per sec of water. This low duty encouraged the study of the local irrigation method. It was found that during 1933-43, extensive experiments had been performed but no collective study of the results had been made. Some experiments were intended to show the influence of different irrigation methods on crop yields. Some were to show the effect of different depths of water. Still others were to determine the best interval between irrigations. The experiments were extensive and the results were interesting. A total of 287 tests were studied, of which 198 were used to compare the crop yields by continuous versus rotational irrigation methods. About one half of the cases showed better yields for rotational irrigation. Of the 198 tests, 142 cases showed yield differences of less than 10% based on the yield by the local continuous irrigation practice, 43 showed differences of 10% to 20%, 9 showed differences of 20% to 30%, 1 showed a difference of 30% to 40%, 2 showed differences of 40% to 50%, and 1 showed a difference of over 50%.

The different irrigation intervals varied from 1 to 15 days. The 3 day interval, or 1 irrigation every 3 days, indicated a higher possibility of better yield than other intervals.

The different depths of irrigation water used in these tests varied from just enough water to prevent the soil from cracking to enough water to keep the field saturated. The intermediate water depths were 0.015 m, 0.03 m, 0.036 m, 0.045 m, 0.06 m, and 0.09 m. For further details, the reader is referred to the Engineering Series No. 3 of the JCRR.[2] From these tests, three conclusions were drawn:

DEMONSTRATION OF ROTATIONAL IRRIGATION

Since the result of the preceding study[2] was made known in 1953, the government and the people began to realize the importance of the problem, especially under the pressure of the over 3% annual increase of population. In 1954, the government established the Rotational Irrigation Promotion Commission (RIPC), the purposes of which were to promote rotational irrigation and to plan and supervise experimental and demonstration farms. Three experimentation farms were successively established. In each farm, a small area was set aside and subdivided into plots for various irrigation treatments, for example, rotational irrigation on 6-day, 8-day, and 10-day intervals and continuous application. Several replications were provided for each different treatment. The amount of irrigation, precipitation, outflow from surplus rainfall, evaporation, sunshine, etc., were all carefully recorded. There were over 10 demonstration

1. As far as the crop yield is concerned, there is no appreciable difference between the two methods;
2. most tests showed appreciable decrease in water depth for the rotational irrigation method; and
3. the tests showed a water saving of 15.8% to 38.7%, with 26.1% as the average for the rotational method.

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[2] "Rotational Versus Continuous Irrigation Methods For Taiwan," by Lee Chow, Engrg. Series No. 3, Joint Comm. on Rural Reconstruction, 1953.

farms throughout Taiwan. On these demonstration farms, the quantity of water, though also measured, is not very strictly controlled. The farms, on one hand, were to show the results by rotational irrigation as compared with the continuous practice, and on the other hand, to exploit actual difficulties when rotational irrigation is to be put in practice on a large scale. For a more detailed description of the experimentation farms, the readers are referred to another paper.[3]

Records, starting in 1955, are available for the experimentation and demonstration farms. Although there was some inconsistency of results due to too many varying factors, two points are clearly verified in a great majority of cases. One is that rotational irrigation does give higher yields and the other is that the amount of water saving is at least 20% to 30%, and sometimes it is as high as 50%.

Rotational irrigation was put into use for the first time on a large scale and its merit was fully recognized in the 1954-55 drought when the rivers and canals had only 1/3 to 1/2 of the ordinary flows. Rotational irrigation had achieved remarkable results. A total of 35 out of 40 irrigation associations practiced rotational irrigation and had a total planted area of 195,959 hectares. If rotational irrigation had not been practised, the transplanted area would have been only 139,797 hectares, or an increase of 51.7% was achieved by rotational irrigation.

Two important actions were taken by the government to help enforcement of rotational irrigation. One was the promulgation of an irrigation regulation in February, 1955. This regulation has special reference to rotational irrigation. The main purpose of it was to legalize the features involved in implementation of rotational irrigation. This was the first time that irrigation in Taiwan had regulation. The second was the authorization of a four-year plan in which a total of 112,808 hectares of paddy field are to be provided with new, or strengthened with improved, irrigation systems in order to enforce rotational irrigation.

DESIGN OF ROTATIONAL IRRIGATION SYSTEM

Different Methods of Rotational Irrigation.—Rotational application of water may be done in the following three ways:

A. Rotation by sections in the main canal,
B. rotation by sections in the laterals or sublaterals; or
C. rotation by farm ditches.

In case A, the water will be conveyed in turn to different sections of the main canal. If the main canal is divided into three sections, the water will be conveyed in turn to the 1st, 2nd, and 3rd sections. In case B, rotation by sections in the laterals or sublaterals, the main canal will have continuous flow while the water will be conveyed to the various sections of laterals or sublaterals successively. In case C, rotation by farm ditch, the water flow in the ditch will be intermittent while the flow in the main, laterals and sublaterals will be continuous. In this case, the whole area is divided into rotation areas. There may be any number of rotation areas. The use of water is rotated in the subdivisions of a rotation area, called rotation units. For example, a certain rotation area is divided into 5 rotation units, and the rotation interval is 5 days,

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[3] "Rotational Irrigation—An Evolution in Taiwan," by Lee Chow, Newsletter of Internatl. Rice Comm., U. N., March, 1958.

each rotation unit will get its share of time of irrigation application in proportion to its area. The sum of all application periods of the rotation units in a rotation area will be the rotation interval.

In the afore mentioned three types of rotation, experience has shown that case C is the best because type A will call for the same capacity for the whole main canal, type B will call for the same capacity for the whole laterals or sublaterals, while case C will have diminishing capacities and call for larger farm ditches. Moreover, case C can be better incorporated into the practice of common irrigators, which will be explained later, than the other 2 types and will not call for enlargement of existing canals when used for rotational irrigation.

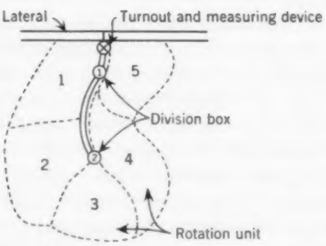

FIG. 1.—ROTATION AREA AND ROTATION UNIT

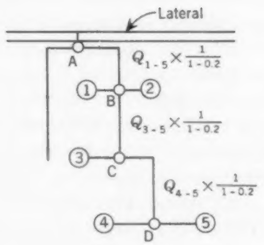

FIG. 2.—DERMINATION OF Q

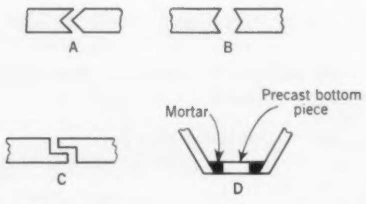

FIG. 3.—PRECAST CONCRETE SLAB FOR LINING

Rotation Area and Rotation Unit.—In the design of a rotational irrigation system, the first step is to determine the size and location of the rotation areas. There is no fixed rule for the best size. The layout should be planned according to topography, existing roads and water courses, nature of soil, and other ground features. Experience has shown that the size of 50 hectares is on the average a good rotation area size. It should be noted, in general, that a rotation area should not be too large to require a discharge in the rotation area canal which cause erosion. Also a rotation area should not be too small as to call for a very small amount of flow because, in case of a very long ditch, there would be

serious difficulty in flow conveyance. Fig. 1 shows the general idea of how the rotation area and the rotation units are laid out. The symbol X denotes the turnout structure and the measuring device, "1" denotes a division box from which water is delivered in turn to rotation units 1 and 5. Division box "2" denotes another division box where water is delivered in turn to rotation units 2, 3, and 4. If the rotation interval is 5 days, and, for the sake of simplicity, the rotation units are all of the same size, it would result that all the 5 rotation units will have equal share of time, that is, 1 day, In case of discharge fluctuation, the irrigation schedule should then be changed to fit that particular situation. If there is precipitation during irrigation, the schedule is also changed to save water.

Determination of Canal Capacity.—The proper way to determine the canal capacity is to start from the lower end and work backwards. The following formula has been used:

$$Q = \frac{A}{8.64}\left(\frac{d_s}{p_s} + \frac{d_r}{p_r}\right)\frac{1}{1 - L} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

in which Q is the required discharge in cu m per sec, A is the irrigated area in hectares, d_s is the depth of water in meters required for soaking the field, varying from 0.12 m to 0.15 m in the local farming practice, d_r is the depth of water in meters for each application, p_s is the period of soaking the field in days, p_r is the rotation interval in days, and L is the canal conveyance loss in percentage. The water depth d_r varies with the crop, the nature of soil, and other factors. In the rotational irrigation schemes, in Taiwan, the water depth used for each application varied from 0.03 m to 0.06 m. The rotation interval p_r varied from 2 to 8 days, with the 6-day interval being most common. The soaking period, p_s, varies with the soil structure and it is usually around 20 days. For sandy soil, soaking may not be required. It has been found that p_s could be shortened to less than 20 days, whereby further water saving could be effected. The rotation interval, p_r, after having been determined, is to be closely investigated and adjusted, if necessary, during irrigation operation. At the end of the rotation interval, if there is still some water left from previous application, or the field is still wet, it would mean that either the depth of irrigation ought to be reduced or the rotation interval ought to be lengthened. The canal conveyance loss, L, may be assumed at first by the designer and should be checked by the irrigation operators and modified to conform with the actual conveyance loss.

Fig. 2, shows five rotation areas. The discharges required for each area are calculated first using Eq. 1 without the loss factor 1/1-L. The Q between C and D will be Q_{4-5} times the loss factor. The Q between B and C will be Q_{3-5} times the loss factor. The Q required between A and B will be $Q_{1-5}\left(\frac{1}{1-L}\right)$.

Structures and Measurements.—The design of the structures in a rotational irrigation system is not different from that in other types of irrigation systems. The following 5 items are examined with the hope of casting some light on future improvement.

A Turnout gates.—Either in new rotational irrigation systems or in remodelling old systems, turnout gates are the most common installation. Without these, the water for a rotation area cannot be regulated or controlled. It has been

FIG. 4.—TURNOUT GATES

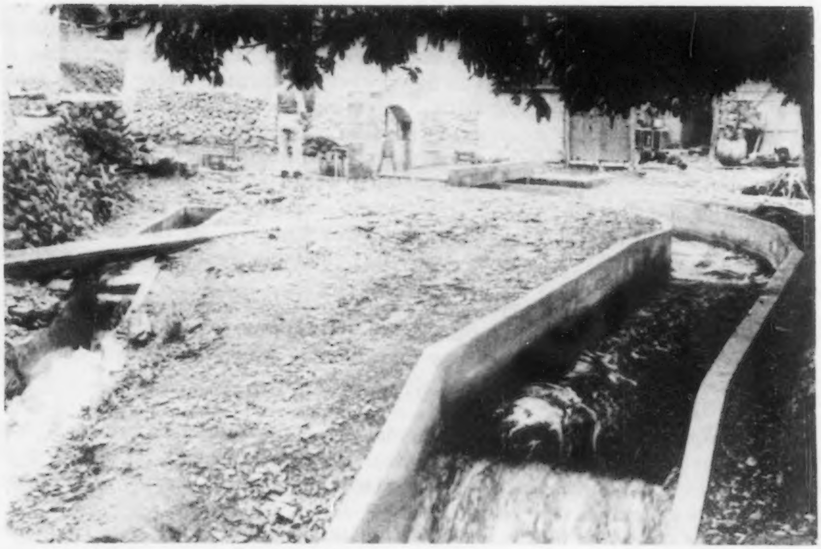

FIG. 5.—TURNOUT GATE WITH RECTANGULAR WEIR BELOW

common to remodel the existing systems by combining several laterals into one. These laterals previously tapped water directly from the main canal. In any case, each rotation area should be provided with a turnout gate with a locking device. Several forms of lock are being manufactured in Taiwan. The best one is a combination lock incorporated in the gate hoist. In case the combination number is revealed, the lock can be replaced easily. A standard turnout gate with wedges has been very satisfactorily used, specially for water tightness. Figs. 4 and 5 show such turnout gates.

B. Measurement Device.—In order definitely to control and measure the flow delivered to a certain rotation area, a measurement device is indispensable. Various measurement devices have been used; standard weirs, Parshall flumes, adjustable gates and constant-head orifice gates. The last two will be further explained in the following paragraph. Parshall flumes and standard weirs have been found very successful. In the case of Parshall flumes, attention should be directed to the ease of reading the staff in the stilling well. In the case of the standard weirs, attention should be called to the following points: (1) The distance upstream from the weir to the turnout gate should be long enough to produce a steady, calm flow but not loo long to be inconvenient for the operators who have to walk back and forth between the turnout and the weir for adjusting; (2) the air vent pipe required for the weirs without contractions, that is, of equal width to the canal, should be large enough to produce a true free-fall water nappe. A triangular weir, a rectangular weir, and Parshall flumes are shown, respectively, in Figs. 5, 6, and 7.

C. Combination of items A and C.—Sometimes it is more convenient to use a combination structure to combine the turnout gate and the measurement device. Adjustable weir serves as a turnout as well as a measurement device. The lowering of the adjustable weir increases the flow and the elevating of the weir decreases it. The flow is measured in the same way as in a standard weir. Constant head orifice is another type of combination. It consists of two gates; the upper one is set with a constant head above and below the gate, while the lower one is used to adjust the flow. This constant head orifice is sometimes more expensive than the combined cost of a turnout and a measurement device but is more convenient to operate. The orifice type is also preferable because of the little head required, while the adjustable weir type requires a much larger head.

D. Division box.—Division box is required to facilitate the operation of diverting the flow to various rotation units. Without division boxes, the operators would have to plug or open a farm ditch by hand in which case the operation would be cumbersome and time consuming. One drawback of the division box is that it usually leaks due to too small a pressure against the gate. It is important that the contacting surfaces of the gate and the grooves be extremely smooth and true in dimensions. T. R. Smith, devised an adjustable type of gate which can be operated in small increments of openings. It was not used much because division boxes as used in rotational irrigation systems seldom require partial openings and because of its higher cost. Any improvement on the design of the division box must be economical, simple in design, and easy to operate. These are important because many division boxes are required in any rotation irrigation system. Fig. 8 shows two such division boxes.

E. Lining.—In the rotational irrigation work in the past and now under construction, precast concrete slabs have been used to advantage. (Fig. 9) It is economical and does away with the difficulty of mixing small amounts of concrete in scattered places and, most important of all, it renders possible steeper

FIG. 6.—TRIANGULAR WEIR

FIG. 7.—PARSHALL FLUMES

canal side slopes. This is specially important where the land value is high. The thickness of the precast slabs varies from 5 cm to 7 cm. Some of the earlier slabs were imbedded with galvanized wire but later this was found to be unnecessary. Breakage of the slabs in handling and transportation can be reduced to a negligible percentage, if handled with care. It is to be noted that a firm earth backing for the slabs is absolutely necessary. Various joints as shown in Fig. 3 have been used. The type in Fig. 3(b) proved to be the best. It is also a common practice to use precast slabs for the sides and to cast the bottom in place. In case of a precast slab bottom, cement mortar should be used to fill up the corners as shown in Fig. 3(d).

OPERATION OF ROTATIONAL IRRIGATION SYSTEM

Irrigation Schedule.—Before irrigation is started, an irrigation schedule is prepared. This schedule will give all the names of the water users, the land number and area, date and hour of their turn to use the water, the number of the turnout gate which releases water to the land, etc. In case the canal is carrying a smaller quantity of water, for example in a dry year, this schedule will have to be changed. In that case, the quantity of irrigation water will be reduced either by a reduction of the depth of application or by a lengthening of the rotation interval. When the irrigation system has a reservoir and the reservoir, by chance, has only a partial storage, then the best effective use of the available water supply can be easily planned. This schedule is posted and made known to the water users. In Taiwan, this operation is done by the irrigation associations. There is a total of 40 irrigation associations which have the responsibility of operation and maintenance of all the irrigation systems.

Common Irrigators.—In the earlier period of practicing the rotational irrigation, the farmers, during their turn of applying irrigation water, had to come out to their fields to take care of diverting water, distributing water, maintaining ditches, etc. Later on in southern Taiwan, in the Chianan Irrigation Association area, there developed a practice of using common irrigators within a rotation area. These common irrigators, selected by the farmers within the rotation area, were hard-working, impartial, honest and familiar with the whole area. For each rotation area of 50 hectares, two common irrigators are required. The irrigation of the whole area would be under their charge. They would see that a particular lot of land needed some adjustment in the rotation interval or in the amount of irrigation according to the soil or to its appearance. The common irrigators may have difficulty at first distributing the water satisfactorily, but it will not take them long to become experienced.

In the practice without the common irrigators, an average farmer, farming about 0.33 hectares, has to go out to his field about 15 times during one rice crop irrigation season of about 90 irrigation days. Each time he has to spend about half day. The total man-days for a 50-hectare rotation area will be 15 x 0.5 x 50/0.33 or 1,125 man-days. If common irrigators are used, the total number of man-days in the same area in the same period will be 90 x 2 ot 180. So the saving of man-power is appreciable. What is more important is that a better irrigation job can be done. This explains why the practice of common irrigators is spreading very rapidly in Taiwan. It naturally reduces the agricultural population. The people who previously were engaged in agriculture can now help in industrial or other development work.

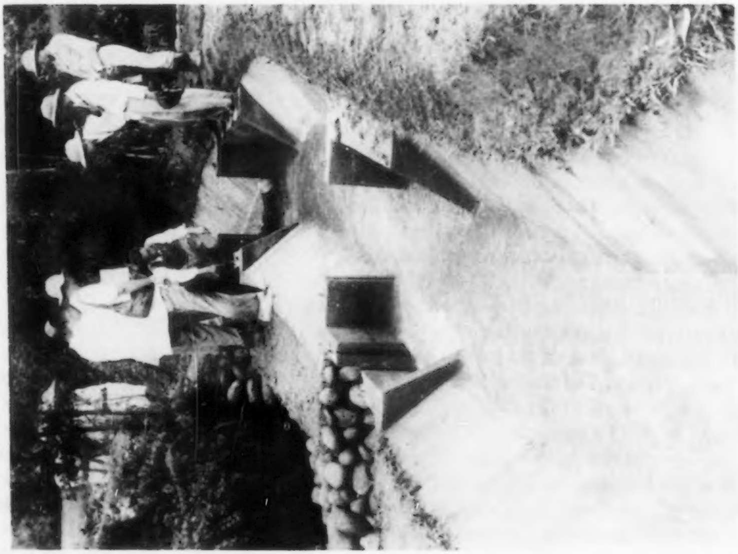

FIG. 8.—DIVISION BOXES

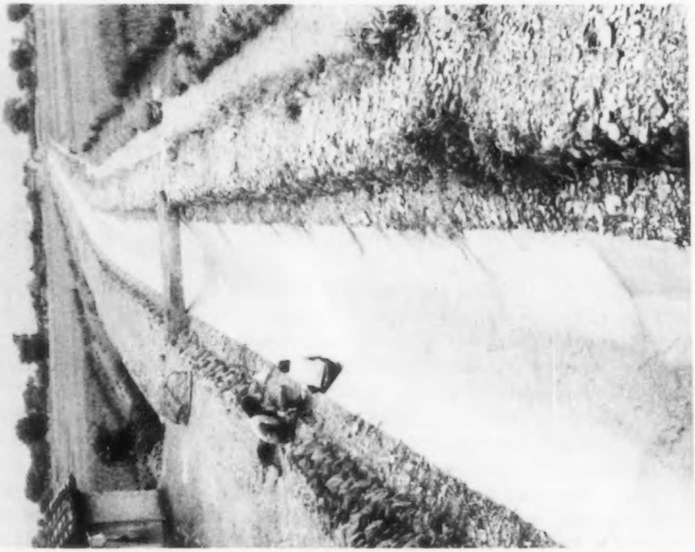

FIG. 9.—PRECAST CONCRETE SLAB LINING

Operation of Gates.—The operation of the turnout gates is in the hands of an irrigation assistant employed by the irrigation association. He is the man who knows the numbers of the combination locks and has the responsibility of releasing the proper amount of water through each turnout. The division boxes are operated by an irrigation subcommittee the members of which are elected by the farmers. Where there are common irrigators, the division boxes will be operated by the common irrigators. The irrigation period each rotation unit is entitled to have is clearly in the minds of the division box operator. Any improper operation will be self checked by the farmers themselves. Very little dispute has been reported.

Training of Operators.—Since 1956, each irrigation association has started training classes in which graduates from agricultural vocational schools have been selected for training. The techniques of operating the gates, using and reading the various measuring devices, making discharge adjustments, and all other operation details are explained and practiced in service.

IMPROVEMENTS TO BE MADE

Closer Capacity Determination.—As already indicated, the canal capacity required can be more closely determined if all the factors in the discharge formula can be better known. Proper water depths and periods for soaking the field and for each application would depend on close observation of the engineers in canal operation. Actual canal conveyance losses should be measured and used for releasing an adequate amount of water.

Better Operation for More Effective Rainfall.—The higher the effective rainfall, the less the artificial irrigation. Whenever there is precipitation, the gates of the irrigation system should be so operated as to reduce the released amount of water or to cut it out entirely. The importance of this can be very easily realized and appreciated when the irrigation system contains reservoirs or other storage facilities because the water thus saved can be stored for later irrigation use. Even where the system is without storage facility, the importance and necessity of increasing the effective rainfall still exist. For example, a river supplies a number of irrigation system and the river covers a long distance and drains a large basin. Very often the rainfall only covers a small area. Saving of irrigation water on the upstream area may help greatly on the water shortage in the downstream area. In a basin-wide development involving multiple uses of the water resource, the saving of irrigation water may be of appreciable help on other uses, for example, on hydro-electricity generation.

Joint Research for Irrigation Engineers and Agriculturists.—Rotational irrigation seems to have a wide field of improvement requiring the joint effort of irrigation engineers and agriculturists. Farming methods, such as proper field soaking, improvement, and extension of common seedling beds, proper irrigation to suit crop physiology, etc., need further research. Common seedling beds have been suggested for better control on seed treatment, for better preparation of the beds, and for other farming practice such as proper age of seedlings for transplantation. Common seedling beds can very well be incorporated into rotational irrigation practice because the age of the seedlings can be perfectly controlled to fit the irrigation schedule. The cooperation between the farmers by forming into teams mutually to help one another in transplanting can also be better worked out to fit the age of the seedlings and the irrigation

schedule. To transplant the seedlings at the proper time is very important in rice culture. It would be very interesting if some research program work laid out trying to devise an irrigation pattern to conform with the water requirement and water absorption capacity of various plants on the basis of plant physiology. Rice has been found in the Taiwan Agriculture Experiment Station to have a definite period in its growth in which the capacity to absorb water is the highest and another period in which the rice crop demands drainage. There may exist some special pattern of irrigation which would require the least amount of water and yet would give the highest yield.

Journal of the

IRRIGATION AND DRAINAGE DIVISION

Proceedings of the American Society of Civil Engineers

GEOPHYSICAL PROCEDURES IN GROUND WATER STUDY

By H. R. McDonald[1] and Dart Wantland[2]

SYNOPSIS

Although geophysical methods of subsurface exploration were developed primarily for, and have been used most extensively by, the petroleum industry, many of the procedures apply equally well in the search for ground water. The principles of the geophysical methods most useful in ground water exploration are described and illustrated. In addition, a new application of the electrical bore-hole logging is described which may be of great importance in locating leaky zones in irrigation canals.

INTRODUCTION

Most engineers engaged in ground-water investigations have some general knowledge of geophysical methods. However, in many cases, the use of potentially valuable geophysical tools is overlooked because what they can do to help locate suitable aquifers is not generally understood.

For this reason, the purposes of this paper are as follows:

1. To explain briefly the principles of those geophysical methods most useful in ground-water investigations;
2. To illustrate the use of these methods by examples;
3. To discuss a new development in geophysics which may have application to irrigation and drainage problems.

Note.—Discussion open until February 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 3, September, 1960.

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Although geophysical exploration was mainly developed, and has been most widely used in the search for oil, much of the knowledge thus gained, and many of the procedures employed apply equally well in the ground-water field.

THE GEOPHYSICAL METHODS

The water-well driller has different sets of tools with which to put down holes. He may use cable tools or a rotary rig or select a rock bit or a diamond bit as most suitable to a drilling problem. In like manner, the geophysicist has sets of tools or exploration procedures with which to probe beneath the surface. He may use one of four major geophysical methods—the seismic, the electrical, the magnetic, or the gravity method—whichever is most suitable in a given case.[3,4]

The Seismic Method.—In the seismic method, the speed of travel of seismic waves in different subsurface layers is measured. The waves are created by exploding small charges of dynamite buried in shallow holes. The depth to these layers and their thickness are also measured and such geophysical data can be correlated with definite horizons established by drilling. We know, for instance, that seismic waves travel faster in consolidated rock than in unconsolidated overburden. Therefore, a layer in which seismic waves travel at a high velocity may be bedrock in a buried channel. Mapping such a channel by seismic measurements, using the "refraction" procedure, may establish where water bearing gravel has the greatest thickness and, hence, the best place to drill.

The Electrical Method.—In the electrical method, most used in ground-water investigations, direct current is sent through the ground between two metal stakes. This permits the electrical resistance or resistivity of earth materials to be measured. Resistivity is a definite characteristic of rocks and formations and makes it possible to distinguish different types of materials from each other. For example, dry gravel has a higher resistivity than wet gravel and by way of contrast, clay and silt have a very low resistivity.

In the resistivity method, metal stakes, through which the electrical current enters the ground, are moved farther and farther apart in the course of making a set of measurements. As a result of this movement the current goes progressively deeper. In this way, the resistivity of a larger and larger volume of earth is measured and data are obtained with which to plot a resistivity depth curve. Such measurements have been called "vertical electrical drilling." Field results can be correlated at drill holes and the depth to horizons determined, as related to ground water.

The Magnetic Method.—In the magnetic method, a magnetometer is used to measure the vertical component of the earth's magnetic force at stations in an area. (The horizontal component of the earth's magnetic field is the one which causes a compass needle to point to the north.)

The magnetometer can be employed to study subsurface conditions because the magnetic properties of rocks are indicative, in many cases, and measurably affect the earth's magnetic field. For example, a basalt dike is almost invariably highly magnetic. A basalt dike, therefore, can often be traced by magnetic measurements, even though it is buried, because magnetic force is a maximum at points on the surface near to and just above it. Correlations can be established at drill holes and outcrops to guide the interpretation of magnetic surveys.

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3 "Geophysical Exploration," by C. A. Heiland, Prentice Hall, Inc., New York, 1940.
4 "Exploration Geophysics," by J. J. Jakosky, Times Mirror Press, Los Angeles, 1940, Revised Edition, Trija Publishing Co., Los Angeles, 1950.

Ground-water geologists are familiar with the "barrier action" of dikes which may dam up underground water and cause it to be impounded in adjacent pervious formations. In other cases, water may accumulate in fractured contact zones between dikes and neighboring impervious beds. The magnetic mapping of dikes is an accepted geophysical tool in ground-water exploration.

The Gravity Method.—In the gravity method, the force of gravity is measured at stations on traverses with a gravity meter. Gravity meter measurements supply subsurface information because the density of layers or rocks of different kinds, and marked contrasts in density, also affect the force of gravity in a local area. This is illustrated by the use of a gravity meter to trace buried dikes (which is possible because the dike rock has a high density), which causes an increase in gravity force near the dike. The gravity meter can also be used to show the configuration of a relatively high density bedrock surface along a buried channel or in a sedimentary basin. Both of these applications are useful in finding ground water. Correlations of gravity measurements can be made at drill holes and outcrops just as in magnetic surveys.

General Considerations.—The preceding indicates that all geophysical methods have three common characteristics. They require; (1) certain measurements to be made at the ground surface using special instruments, (2) that these measurements relate to, or reflect properties of, buried rocks and formations or structural conditions, and (3) that these relationships permit the geophysical data to be interpreted in terms of subsurface geology.

That geophysical findings of a survey should be correlated with drilling or outcrops has been referred to. Such drill hole correlation, by which the significance of subsurface horizons can be verified, lends strength and certainty to geophysical results.

Geophysical exploration can be defined as a type of field investigation where measurements are made at the ground surface with special instruments to secure subsurface geological information.

Basis of Application.—Knowledge of the geology of an area is essential to the understanding of the occurrence of ground water because geologic structure and stratigraphy provide the framework in which ground water, recharge, storage, and discharge take place. Therefore, any process that increases our knowledge of geologic conditions will help the investigator to determine the likelihood of the occurrence of ground water in a given area. It will help him to determine whether ground water may occur in small or in large quantities, whether the ground water is sweet or saline, and whether the geologic formations are likely to yield water to wells freely.

Inasmuch as the geophysical methods previously described will, under certain conditions, contribute to a better understanding of the geology of an area, they are useful tools in ground-water investigations.

The authors do not mean to imply that geophysical methods may or should replace other means of exploring for ground water. We wish to bring out that, in many cases, geophysics can be used quite advantageously to supplement the procedures usually employed for such purposes.

EXAMPLES OF GEOPHYSICAL INVESTIGATIONS

There are numerous examples of the successful employment of geophysical methods in locating ground water and/or the best place or places to drill in order to find ground water. These examples are described in technical arti-

cles scattered through a variety of publications. To specifically illustrate the manner in which geophysical field investigations were applied to particular ground-water problems, two examples from investigations made by the United States Bureau of Reclamation, Dept. of Interior (USBR) are presented.

Weber Basin Project.—The Weber Basin Project of the USBR is now (1960) under construction. It is designed to irrigate more than 54,000 acres of new land and supply supplemental water to some 24,000 acres now short of water. The project area contains the major concentration of population in the state of Utah, where municipal and industrial demands for water are growing rapidly. Even with the increased water to be supplied by the project works, there currently is need for additional water.

The area east of the shore of the Great Salt Lake is underlain by an artesian basin that extends over some 200 sq miles. Water from artesian aquifers supplies many farmsteads as well as several cities. In certain local areas, these aquifers contain slightly brackish water.

To test the ground water possibilities of the basin, two wells were drilled by the USBR in 1955, to depths of 1,220 ft and 977 ft, respectively, using cable tools. It was decided to explore for deeper aquifers, and, subsequently, a third well was drilled, using a rotary rig, to a depth of 3,006 ft. Prior to drilling it, however, seismic and gravity meter surveys were conducted to secure information on the depth, thickness, and continuity of aquifers and the configuration of the basement rock. These surveys were made to aid in selecting the best location for this deep test well.

Geologic conditions.—The "East Shore Area" in which the city of Ogden, Utah is located, is bounded on the west by the Great Salt Lake and on the east by the steep slopes of the Wasatch Mountains. These mountains are composed of formations ranging in age from pre-Cambrian to the present. The formations include metamorphics such as gneiss, quartzite, and schist, as well as sedimentaries, such as conglomerate, shale, limestone, and tuff. The Weber River is the principal stream to enter the east side of the Great Salt Lake. It flows from the Wasatch Mountains in a generally westerly direction across the area and is joined near Ogden by its main tributary, the Ogden River.

In past geologic times, the Weber River and other streams have deposited eroded material to depths of several thousands of feet in the basin of ancient Lake Bonneville and its remnant, the Great Salt Lake. The highest shore line of the once extensive Lake Bonneville was at an elevation of about 5,200 ft, and the present elevation of the Great Salt Lake is about 4,200 ft. The steep front of the Wasatch Mountains shows a number of remnant shorelines at different elevations. Broad alluvial benches and terraces extend westward from the mountains.

Geologically, the significant features of the area are as follows:

1. The Wasatch fault, which is roughly parallel to and just west of the Wasatch Mountains.

2. Little Mountain, a pre-Cambrian block that rises a few hundred feet above the surrounding plain and is located about 15 miles west of Ogden, and near the shore of the Great Salt Lake.

3. The section of lake basin sediments—several thousand feet thick—deposited in the Bonneville-Great Salt Lake Basin. This section contains numerous artesian aquifers.

Several hot springs in the area support the belief that warm mineralized water rises from considerable depth along the (Wasatch) fault zone and is one source of the ground-water contamination, or brackish water, referred to.

Geophysical investigations.—Geophysical investigations were made on the Weber Basin Project during a 6 weeks period in the fall of 1955. The seismic reflection method—widely used in searching for oil—was employed to measure the depth to sand and clay layers and trace them from point to point in the area, and thus provide subsurface information. A set of "shallow" seismic reflection equipment was loaned to the USBR, Dept. of Interior (USGS) by the Geophysics Branch of the United States Geological Survey. That organization also made available the services of an experienced geophysicist to assist in starting the work.

The geophysical investigations were cooperative in another respect. At the time the seismic work was underway, the USGS was conducting gravity meter field studies in the area. In the course of these studies, a reconnaissance gravity meter survey of the area was made in which the USBR was interested. A copy of this map, which supplied a broad picture of the slope and configuration of the basement rock in the basin, was made available to the USBR.

Seismic reflection method.—The seismic reflection method is basically similar to marine "echo sounding," whereby the depth to the ocean floor is determined. To make an echo sounding, the time, in seconds, is measured for a pulse of energy sent from a vibrator in the hull of a ship to travel to the floor of the ocean and back to a vibration detector, which is also in the ship's hull. To convert this reflection time to the depth of the ocean floor, one-half of the measured time is multiplied by the speed with which the vibration travels in sea water.

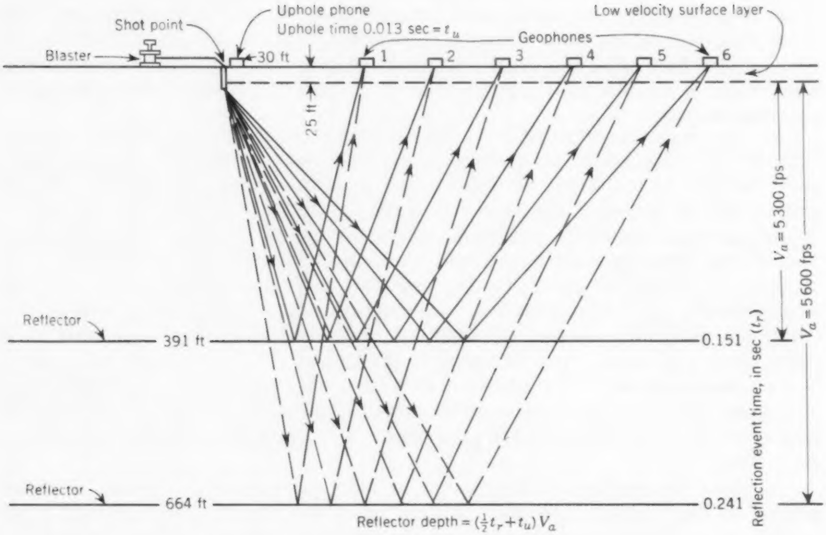
To apply the reflection procedure to map subsurface horizons, such as gravel or clay layers, one-half of the "reflection event" time obtained from the seismic record is multiplied by the speed of seismic waves through the layers involved. The seismic reflection method is illustrated in Fig. 1. On the seismic reflection record, the arrival of reflected seismic wave energy at the geophones is shown by the sharp down-break in trace lines on the seismic record. Time of the reflection event can be scaled to 0.001 of a second.

Seismic field operations.—The first seismic lines were placed near the two deep drill holes put down by the USBR. The seismic records showed numerous reflections from various subsurface horizons. This was significant because it was not known, before the survey was undertaken, if the lake sediments would yield reflections.

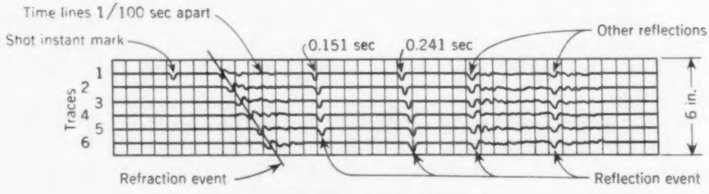
Early in the survey, the speed with which seismic waves travel in the lake beds was measured in three deep drill holes to ascertain the value of wave velocity to use in computing the depths to the different reflecting layers. These velocity measurements were made by lowering a special seismic wave detector, or "geophone," into the drill hole to a measured depth and timing the wave from an explosive charge detonated in a shallow "shot hole" at the surface.

Correlation of reflections and depths to sand and clay layers, shown on drill logs, was studied carefully in the beginning of the investigation because it was a critical point as to the usefulness of the seismic method in this problem. It was found at one drill hole, for example, that twelve reflections were "picked" from the seismic records, which came from depths of 213 ft to 1,130 ft. The total depth of this drill hole was 1,200 ft. These twelve reflections correlated with the logged depths to changes from sand to clay or clay to sand, and so forth. The maximum discrepancy in correlation was 7 ft.

Correlation of reflections.—Study of the reflection seismograms and drill logs showed that a sufficiently close agreement was demonstrated to permit reflections and/or the beds of sand or clay to which they related, to be correlated between seismic stations—or "spreads"—that were from 1/2 to 1-1/2 miles apart.



(a) EXAMPLE OF DEPTH CALCULATION



(b) SEISMIC REFLECTION RECORD

FIG. 1.—SEISMIC REFLECTION METHOD

In the course of the seismic survey, seventy-four depth determinations and three sets of drill hole velocity measurements were secured. These depth points were established on seismic spreads located along traverses which followed section line roads across the area. These traverses permitted reflection cross sections to be drawn which were tied to basement rock at the outcrop and/or to deep wells. A total of over 60 miles of exploration traverse

was completed. One of these reflection cross sections is shown in Fig. 2. The reflection depths on the cross section are plotted from ground surface and do not necessarily relate to the scale showing depth in feet.

Deep reflections.—On some of the traverses, reflections were observed on the seismic records that came from depths of 4,000 ft to 6,000 ft or more. These depths were greater than the maximum of 3,000 ft to which it had been possible to measure wave velocities directly in deep drill holes. To determine the velocities assumed in order to compute the depths of these lower reflectors, an approximate method, based on data from the seismic records themselves, was employed. There was difficulty in bringing out and accentuating these deep reflections because the instruments were not designed for investigations at such depths.

In the area, reflections were obtained from depths of from 100 ft to 200 ft, or less, up to and including depths of several thousand feet, as noted. Because there was interest mainly in the shallow reflections, the equipment employed was the type most suited to that problem. The survey demonstrated that the "shallow reflection" seismic equipment is applicable to ground-water investigations in artesian basins. It was also demonstrated that reflections could be obtained from the thick section of lake basin sediments.

Gravity meter survey.—Contours of the value of gravity are shown on the USGS gravity map, previously referred to, which is presented as Fig. 3. The gravity meter survey outlined the subsurface basin and the configuration and slope of the basement rock surface over a considerably larger area than could have been economically mapped using the seismic equipment. The gravity survey indicated that the basement rock surface dips toward the lowest part of the basin, not only from the east and from the west, but also from the north and the south along the axis of a subsurface trough. These dips were confirmed by the seismic findings.

The relation of gravity force to the depth of the basement rock is that at any station where a gravity meter is set up the gravity as measured will reflect the average density of the column of material from the surface down. Since pre-Cambrian rocks of the Wasatch Range and of Little Mountain are of a higher density than lake basin sediments, gravity meter readings near the mountains and in the vicinity of Little Mountains will have a high value. Gravity meter readings at points near the geographic center of the structural basin will have low values of gravity in keeping with the thick section of light sediments below them.

The contours in Fig. 3 are in gravity units—relative to an assumed value of gravity at a base station. One gravity unit = 0.1 of a milli-dyne of force. These contours show the so-called "Bouguer anomaly" values. It is of historic interest that gravity field investigations were not possible until an instrument of the necessary accuracy had been developed, which was in about 1900, in Hungary. This instrument was the torsion balance perfected by the physicist, Baron Roland Von Eotvos.

USBR deep test well.—A third test well, previously referred to, was drilled by the USBR to a depth of 3,006 ft using rotary drilling equipment. It was located on the basis of information supplied by the geophysical surveys.

As part of the drilling contract, an electrical log of the hole was specified which included; (1) measurements of natural electrical current—"Spontaneous Potential," shown on the resulting electrical log as the "S. P. Curve," (2) measurements of the electrical resistivity of formations using various spac-

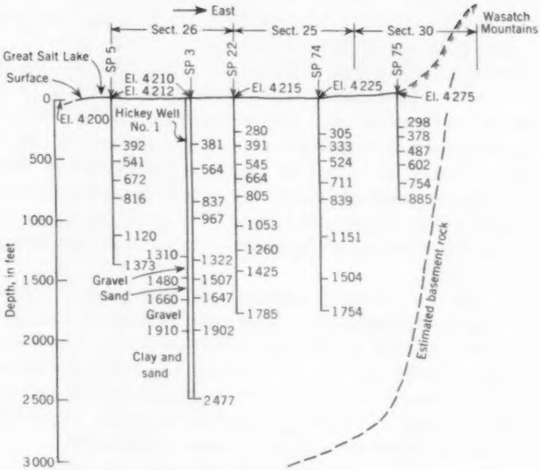


FIG. 2.—REFLECTION CROSS SECTION VV'

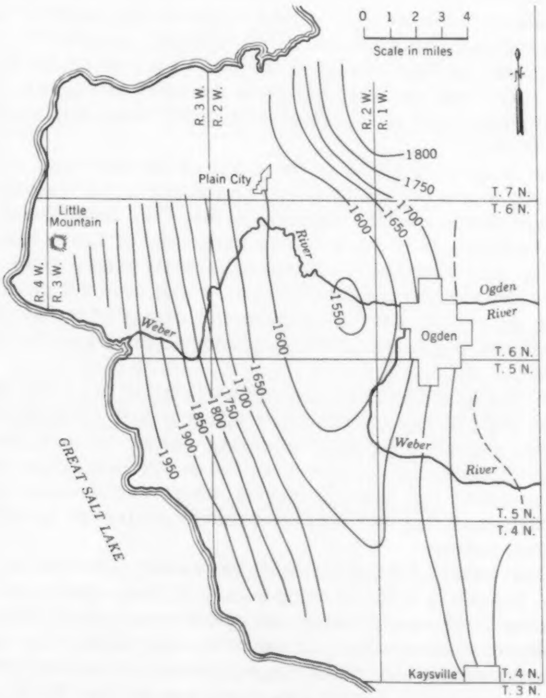


FIG. 3.—GRAVITY CONTOURS IN THE EAST SHORE AREA

ings of the three contact electrodes that were sent down the drill hole, and (3) a "caliper log" by which variations in drill hole diameter are measured by spring-actuated contact points on a special tool that traverses the drill hole. In bore hole logging all quantities measured appear as separate lines on the graphic logs obtained.

Special tests in deep drill hole.—In the course of drilling the deep test well, a number of potential aquifers from a depth of 900 ft to the bottom of the hole were indicated by the electrical logs. Since the well was drilled by the rotary method, as noted, it was deemed advisable to make drill stem tests on zones identified as the most favorable aquifers. Depth points for setting the side-wall packers for these tests were selected on the basis of interpretations of the caliper and resistivity logs.

In addition, the S. P. curve from the electrical log indicated that the water in the aquifers below 1,400 ft was of questionable quality. The drill stem tests enabled us to secure samples of the water from these aquifers for chemical analysis. The drill stem tests also provide information on, (1) the static fluid pressure in the aquifer, (2) reduction in pressure with time after discharge is stopped. Approximate values of porosity in percent and permeability in millidarcies were supplied by the logging operators, on request, for different sections of the drill hole. These data were determined from the operators' analysis of the electrical logs.

The results of the electrical logging and special tests illustrate that methods commonly employed in oil field practice are also useful and applicable in ground-water investigations.

Summary.—As a result of the geophysical field studies, the following conclusions were reached:

1. Reflections from layers at various depths within the 1,220 ft of sediments drilled at one USBR test hole could be correlated with sand and/or clay layers shown on the drill log. Numerous reflections from below 1,220 ft and to 4,120 ft suggested that there were 2,900 ft of sediments composed of sand, gravel, or clay layers which were not tested at that location.

2. Reflections within the 977-ft section drilled at another location were correlated with logged and known changes of material. Numerous reflections between depths of 977 ft and 5,310 ft suggested that about 4,300 ft of section that likewise might contain sand, gravel, or clay layers were present at that location.

3. Reflection cross sections on which the "estimated basement rock line" was shown, indicated that the basement rock surface dips east from Little Mountain, located west of Ogden, and dips west from the Wasatch Mountains. Outcrops of basement rock at these two localities established a subsurface basin or deep trough whose axis runs roughly north-south through the major portion of the East Shore Area. It was concluded from the reflection data that the basement rock might be as much as 6,000 ft deep in the bottom of the trough, which lies some 5 miles west of Ogden.

4. The gravity meter survey of the East Shore Area outlined the artesian basin and showed the configuration of the basement rock surface in some detail. The gravity meter data effectively supplemented the information secured by the reflection seismic survey as to the position of the lowest portion of the basin and the direction of its axis.

The joint use of these two geophysical methods was shown to be advantageous in ground-water investigations of such artesian basins.

5. The electrical and caliper logging of the deep test hole indicated that several aquifers suitable for further testing were present at certain depths. The logging also suggested the quality of the water contained in these aquifers and supplemented the data obtained from the drilling. Subsequent drill stem tests supplied detailed information on the aquifers selected for study.

Resistivity Field Work in South Dakota.—Resistivity field investigations were carried on almost continuously, from the fall of 1951, through 1953, as part of a ground-water and drainage investigation in the vicinity of the city of Huron, South Dakota. The work was on the Oahe Unit of the Missouri River Basin Project of the USBR.

The region, which was studied by geological mapping, drilling and resistivity depth measurements, lies between Huron, in the east central part of South Dakota, and the city of Redfield, some 36 miles to the north. The area investigated was some 30 miles wide and comprised approximately 1,100 sq miles. A contiguous area north and west of Redfield, containing some 900 sq miles, was investigated somewhat less extensively.

The entire region was covered at various times, in past geological ages, by continental glaciers. When the glaciers retreated for the last time, they left a mantle of glacial drift which varied from a few feet in thickness to a maximum of 300 ft. The Pierre shale, of Cretaceous age, lay beneath the drift at an average depth of 90 ft, according to drill tests.

The drift, from the surface down, consisted of the following; a) an average of some 50 ft of glacial till which was mainly clay, b) a variable thickness of sand or predominantly sandy material which ranged from 7 ft to 155 ft, and c) clay, till, silt, or silty sand, above the shale. The sand bodies carried water and might be essentially continuous over areas of several sq miles. In parts of the area, the sand zones might be lenticular and also separated by layers of till. In yet other localities, the sand might be absent.

The most notable character of the glacial drift was its heterogeneity, both laterally and vertically. These conditions made exploration by drilling difficult and costly. Surface geological mapping was not particularly diagnostic of subsurface possibilities. The resistivity field work was used to supplement core drilling and as a guide in outlining the sand aquifer areas. This was one of the main objectives of the investigation.

The resistivity field crew consisted of four men who worked under the direction of a geologist of the Missouri-Oahe Projects Office. During a 9-month period, prior to August, 1953, they completed over 700 resistivity depth measurements, and, in total, over 1,200 such measurements were made. These measurements were closely tied to the exploration drilling to establish and check criteria for the interpretation of the resistivity depth curves. This procedure was continued during the entire investigation.

It was found that the resistivity depth curves would indicate: a) whether sand was present at a test locality and if so, at approximately what depths. Fig. 4(a) is an example of this condition. The curve of Fig. 4(a) shows the relatively high resistivity of sand; b) whether no sand was present and whether the section was all till above the shale, see Fig. 4(b). The curve of Fig. 4(b) shows the typically low resistivity of glacial till; c) within limits, whether the sand was "clean" as shown by relatively high resistivity; d) also within limits, whether the sand was "dirty" and contained appreciable amounts of silt or clay as shown by a relatively low resistivity; and e) quite unmistakably if the water table were below the top of the sand body as shown by Fig. 5. The curve of

Fig. 5 shows very high resistivity due to dry sand above the water table. Note the small scale of Fig. 6 in comparison with that of Figs. 4 and 5.

The resistivity measurements were not considered as a substitute for, but as a supplement to, drilling. A careful study of the first five hundred resistivity depth curves and the logs of the sixty-six drill holes that provided specific check points, showed that in fifty-three cases, or over 88%, the resistivity measurements gave results that definitely could be correlated with the drill logs. For example, where sand was indicated by the resistivity curve, sand was logged from the drilling and at appropriate depths. Where the curve indicated the section was all till, clay, or silt, the drill indicated such material was present.

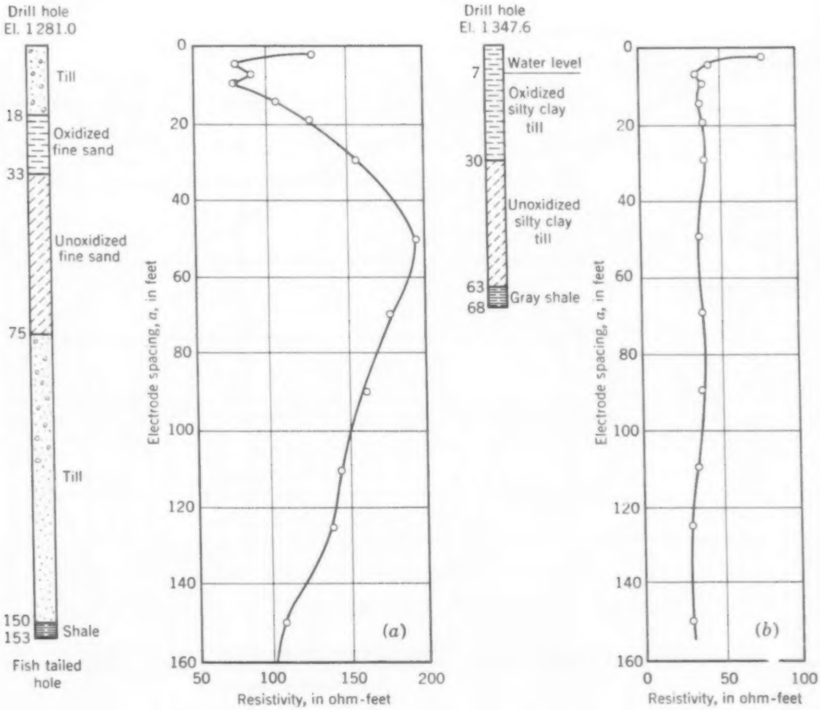


FIG. 4.—RESISTIVITY DEPTH CURVES

In thirteen cases, or some 12%, the correlation was only fair. The resistivity depth curve indications were not "clean-cut" as between definitely sand or definitely clay. These were borderline cases. However, they indicated clearly that drilling was required to learn the true subsurface conditions at these test points.

It was also possible to determine the depth to the shale by resistivity depth measurements. These depths were not required in most cases and depth curves were, therefore, not interpreted for shale depth.

A NEW DEVELOPMENT FOR DETECTING LEAKAGE IN CANALS

The geophysical procedures and their application to ground-water investigations that have been described have followed lines established in oil exploration or the search for ore bodies. A new development is the use of electrical logging in canals to detect leakage.

Field trials of electrical logging to detect probable leaking sections of operating canals were made on the Central Valley Project, California, in October, 1958. The procedure employed was an adaptation of the drill hole electrical logging which has been discussed.

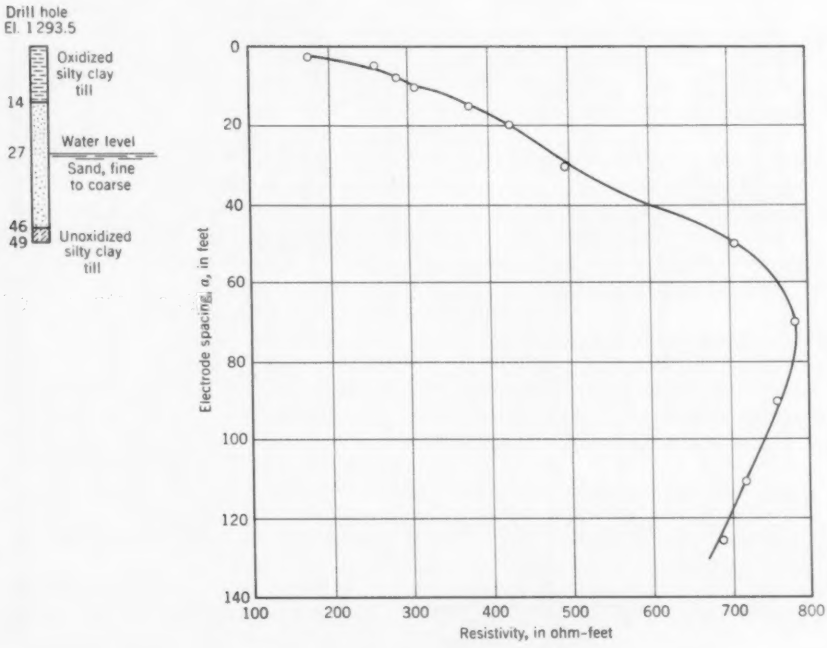


FIG. 5.—RESISTIVITY DEPTH CURVE 32

During the trials, some 7 miles were logged on selected reaches of four major canals that were well suited to such testing. The work was done under the USBR's Lower-Cost Canal Lining Program by a contractor who has specialized in geological and geophysical investigations. How canal logging is done

is illustrated in Fig. 6, in which P is voltage electrode and C is current electrode.

Electrical logging permits the continuous measurement and recording of the electrical resistance (resistivity) of materials comprising the bottom and/or banks of a canal. This is similar to the electrical logging of a drill hole where variations in the materials are shown by differences in measured resistivity.

To log a water-filled canal, contact was made with the ground by four cylindrical lead electrodes which were placed in a line at measured distances apart and laid on the bottom of the canal. The electrodes were connected by rubber-covered wire lines leading to a current source and to recording equip-

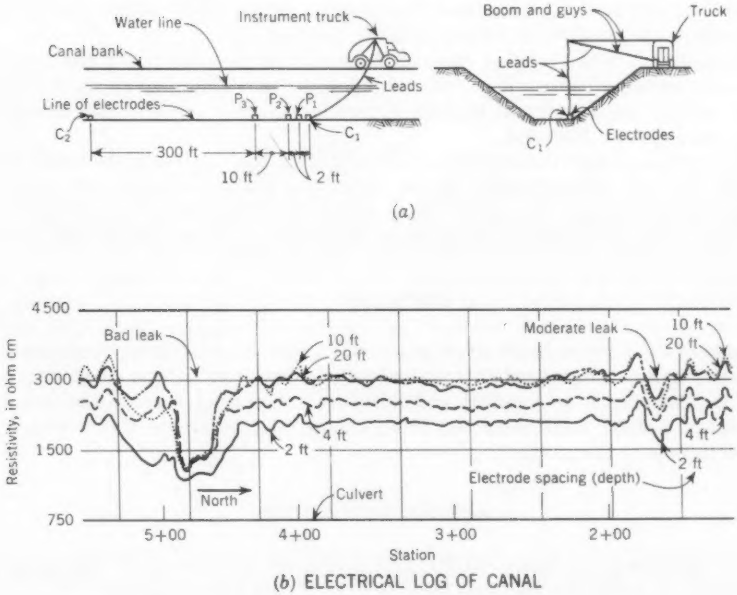


FIG. 6.—ELECTRICAL SEEPAGE SURVEY OF IRRIGATION CANAL

ment in an instrument truck. An electrical current was sent through the ground between the outer pair of electrodes and the voltage between the inner pair was measured as the truck moved along the canal bank dragging the string of electrodes behind it. The electrodes indicated in Fig. 6 were dragged along the west band of the canal just below the surface of the water. Variations in resistivity were shown as variations in measured voltage by the moving pens on the recorder chart, which unrolled as the instrument truck moved forward.

The spacing of the electrodes controlled the depth to which the resistivity of the formations were measured. Logging was done, simultaneously, at a 2-ft

spacing and a 10-ft spacing since the recorder had two pens. A separate traverse was required to log at 4-ft and 20-ft spacings, after changing the electrodes.

Drill hole logging shows that different formations and their character can be identified on electrical logs. In like manner, seepage locations along a canal may be identified if they are markedly different in resistivity from adjacent sections. At present, because of limited experience, it is necessary to correlate very carefully the measured resistivity in a canal section under study with information obtained by drilling.

For example, water lowers the resistivity of earth materials. Therefore, local zones along a canal that show relatively low resistivity, at all depths logged, might indicate seepage. Interpretation must be based on a knowledge of geological conditions and of the material in which the canal is constructed. This is because wet clay, which may be water tight, also shows a low resistivity. In contrast to this, sand and gravel, which show a high resistivity in general, may likewise represent a leaky section.

Results of canal logging tests, and as that previously noted suggests, are on a preliminary basis. It is felt, however, by those engineers most familiar with it, that the electrical logging of canals to detect seepage has promise of being effective to that end.

If it is found that the electrical logging of canals will indicate leaky zones, it will be very advantageous in the operation and maintenance of canal systems. Main reliance is placed on ponding tests to detect leakage and these are quite expensive and require taking the canal out of service during the test.

CONCLUSIONS

Geophysical procedures have been developed largely in the petroleum field. This paper has pointed out that under certain conditions these procedures are also applicable in the location and utilization of ground water. The examples presented herein were selected from among twenty-five or thirty with which the writers are familiar.

ACKNOWLEDGMENTS

The authors are grateful to Mr. Don R. Mabey, geophysicist, and to the Director of the USGS for the map indicated as Fig. 3 in this paper.

Journal of the

IRRIGATION AND DRAINAGE DIVISION

Proceedings of the American Society of Civil Engineers

INSTALLATION OF DRAIN TILE FOR SUBSURFACE DRAINAGE[a]

By John G. Sutton,[1] F. ASCE

SYNOPSIS

This paper reports current progress in installation of tile drains for subsurface drainage. The Soil Conservation Service provided technical assistance on installation of 24,059 miles of tile drains during the 1959 fiscal year. The paper gives benefits of tile drainage, and describes tile used in combination with surface drainage and current procedures used by the Soil Conservation Service in making drainage investigations. Recent changes in the American Society of Testing Materials specifications for clay and concrete drain tile are discussed. Recommendations are given for use of concrete tile under acid and alkali conditions. Recommendations for gravel filter requirements are given.

INTRODUCTION

In a prior paper,[2] the author discussed drainage in the humid areas of the United States. The earlier paper described extent of drainage, some historical developments, drainage enterprises, programs of Federal and state governments which provide assistance, and some of the engineering problems.

Tile drainage systems which are designed to provide drainage for agricultural lands are the subject of this paper. Herein, it is planned to cover in more detail several phases of the practice of tile drainage where substantial progress has been made during the last few years, particularly where current practices have adapted research findings and otherwise differ from published

Note.—Discussion open until February 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 3, September, 1960.

[a] Presented at the March 1960 ASCE Convention in New Orleans, La.

[1] Drainage Engr., Soil Conservation Service, U.S. Dept. of Agric., Washington, D. C.

[2] "Drainage in the Humid Areas of the United States," by John G. Sutton, Transactions, ASCE, Vol. 122, 1957, p. 115.

material generally available. Drainage systems for airports, urban areas and special installations are not discussed.

The Soil Conservation Service in the U. S. Department of Agriculture provided technical assistance on the installation of 24,059 miles of tile drains during the fiscal year 1959. Tile drainage is an essential practice in carrying out a conservation program, because it is necessary for the efficient use of a substantial portion of productive flat lands which are least susceptible to erosion.

In the humid areas, tile for agricultural lands usually consist of either clay or concrete drain pipe, usually 1 ft long, laid in trenches generally 30 in. to 54 in. deep. Nearly all the farm-drain laterals are 4 in. to 6 in. in inside diameter. Mains up to 24-in. diameter, and occasionally larger sizes, are used. In laying drain pipe a small gap is left between the ends of the tile. These gaps permit water to enter the tile. In irrigated areas, tile lines are ordinarily 5 1/2 ft to 8 ft deep. Bell-end and tongue and groove pipe are used extensively in drainage of irrigated lands.

Bituminized fiber pipe is used in many installations in Northeastern states and less frequently in other areas. Plastic pipe has been used in limited amounts. Covered drains of wood box, metal pipe, and other materials are occasionally used.

Tile drains remove gravity water from the soil, stabilize the groundwater table, and collect seepage. Underdrainage is used most frequently in humid areas for imperfectly drained soils subject to a high water table. Such soils need to be permeable enough to permit economical spacing of drains.

In irrigated areas high water conditions are due in most cases to seepage from reservoirs, canals, laterals, and irrigated lands. Saline and alkali salts rise to the surface in many of these areas resulting in extensive damages to crops and land. Most tile installations in western irrigated areas are needed for reclamation or continued use of such lands.

In all cases the values of the crops to be grown must be increased sufficiently to return net profits which can pay off the high investment required for tile drainage. Some soils are permeable enough so that tile drainage is not needed. Other soils may be drained, even though less effectively, by surface drainage with the result that tile drainage is not justified. A thorough knowledge of soils and reactions of soils and crops after tile drains are installed is essential.

BENEFITS AND EFFECTS OF TILE DRAINAGE

The tile drainage of many wet soils results in improved crop yields and more profitable farming. The benefits discussed subsequently are obtained through drainage in conjunction with necessary soil amendments and soil conservation crop rotations.

Soil aeration is necessary for favorable bacterial action and in order to permit rapid diffusion of the soil air to the atmosphere and vice versa. Tile drains aid these processes by lowering the groundwater usually as much as 12 in. to 18 in. within 24 hr after a heavy rain, thereby providing a zone of aerated soil soon after saturation occurs. Tile drains stabilize the normal groundwater at a lower level than in an undrained soil and provide a deeper root zone on the average.

Freezing, thawing, and droughts influence the development of the soil structure and soil permeability following installation of tile systems. In a well-

drained soil, the gravity water moves downward and outward through tile lines instead of saturating the soil and being removed slowly by evaporation and transpiration. The capillary moisture which is utilized by roots of plants is not removed by tile drains.

Tile drainage of wet soils encourages conservation farming, which generally includes the use of grasses and deep-rooted legume crops such as sweetclover and alfalfa. These crops do not thrive in wet soils. The roots of grasses and legumes open up pore spaces in drained soils and encourage formation of soil aggregates. Thus, after tile drainage, the permeability of tight soils improves with conservation farming and good crop rotations.

Well drained soils warm up sooner and can be cultivated earlier in the spring than wet soils. This benefit of tile drainage is especially important in northern climates. The date of seed germination is higher and a good stand of the crop is obtained on the drained soil.

A deep root zone encourages early development of deep-rooted and hardy plants. On well-drained fields, crops are better able to withstand drought due to the deep root system. Soil amendments and fertilizers are utilized effectively by crops grown on a well-drained soil.

The fields can be cultivated with less delay after rains and tractor cultivation is more efficient because the soil dries uniformly and it is not necessary to cultivate around wet spots or parts of fields. Equipment is less likely to mire down. Improved efficiency in cultivation is one of the most important benefits of tiling.

In arid areas widespread salt damage occurs, due to the deposition of salts near the surface from capillary water rising through the soil. Deep drains lower the water table and result in a downward movement of salts in the soil. This lowers the salt concentration in the surface layers of soil and improves crop growing conditions.

The improvement of public health conditions through proper drainage is particularly important in many locations. Tile drainage has an advantage over drainage by open ditches through elimination of standing water where mosquitoes may breed.

SURFACE DRAINAGE NEEDED WITH TILE SYSTEMS

The best drainage is most frequently obtained by a combination of open and closed drains. It is usually most economical to remove surface water from tiled fields by installing shallow surface ditches constructed to grade which do not interfere with cultivation. Land grading and smoothing which eliminate shallow depressions also is beneficial. The surface and subsurface drainage systems are usually complementary on the same area and need to be planned together.

On some soils there is a choice as to whether tile lines or open drains should be used to provide subsurface drainage. Tile drains save land and result in cheaper cultivation. Open ditches spaced closely enough to control the water cut up the field into relatively narrow strips and use much land. Open ditches may harbor weeds and are more expensive to maintain. On the other hand, surface drainage systems are cheaper in first cost and are the only practical solution for some soils. In some areas farming may be carried out initially by improving the surface drainage. Later, it pays to install tile drainage.

Research is needed to determine the increment by which yields of various crops are increased due to tile drainage. One example was an experiment in Ohio in 1958 where corn yielded 120 bushels per acre on a tile drained field with surface drainage and 80 bushels per acre on a field not tiled but having a comparable surface drainage system.

Research also is needed to determine the effective use of land grading and smoothing for drainage used in conjunction with tile drainage. Land grading for drainage in recent years has proven very beneficial. Data are needed to determine areas where land grading and tile should be used together and how specifications for the two practices should be modified when used together.

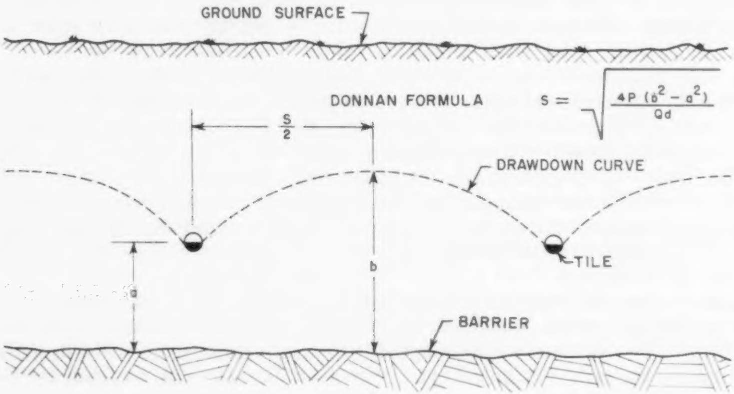


FIG. 1.—TILE SPACING FORMULA

THEORIES OF FLOW OF WATER TO TILE DRAIN

Several theories covering the flow of water to tile drains have been proposed in recent years. Attention is called to the excellent discussion of this subject by J. V. Schilfgaarde, D. Kirkham, and R. K. Frevert.[3] These theories have modified the approach of the drainage engineer towards the solution of many tile drainage problems. Considerable progress has been made towards the rational design of drainage systems using such theories. However, there are still many problems to be solved before a fully rational approach to drainage design is established, including field methods of determining the effective soil permeability.

Among these formulas is the one commonly known as the Donnan Formula,[4] which is typical. The formula was developed for relief drains and is based upon certain barrier conditions. This is illustrated in Fig. 1. The Donnan For-

[3] "Physical and Mathematical Theories of Tile and Ditch Drainage and Their Usefulness in Design," by Jan van Schilfgaarde, Don Kirkham, and R. K. Frevert, Agric., Sta., Iowa State College, Research Bulletin No. 436, February, 1956.

[4] "Drainage Investigations in Imperial Valley," by W. W. Donnan, G. B. Bradshaw, and H. F. Blaney, (10-yr summary), U. S. Dept. of Agric., Soil Conservation Serv., SCS-TP-120, 1954.

mula may be expressed as follows:

$$S = \sqrt{\frac{4P\left(b^2 - a^2\right)}{Q_d}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

in which S = spacing of the tile lines in feet; P = hydraulic conductivity or coefficient of permeability expressed in gal per sq ft per day (Meinzer's Unit); or, cu in. per sq in. per hr usually abbreviated in. per hr; b = distance from the average tile depth to barrier stratum at the midpoint between the tile lines, in feet; a = distance from the average tile depth to barrier stratum, in feet; and Q_d = quantity of water to be drained expressed as gal per sq ft per day (Meinzer's Unit) or in cu in. per sq in. per hr, usually abbreviated, in. per hr.

Where there is no barrier stratum present, a barrier should be assumed at a depth equal to twice the drain depth.

The units for hydraulic conductivity or the coefficient of permeability P and Q_d can both be expressed in gal per sq ft per day (Meinzer's Unit) in Eq. 1; or the values for P and Q_d can both be expressed in in. per hr (cu in. per sq in. per hr) in this formula without changing its validity.

The Donnan and other formulas require that the average effective permeability and barrier conditions be established by field investigations. The hydraulic conductivity of the soil varies greatly within short distances in many soils and it is costly to make adequate number of soil profile borings and permeability determinations to insure an accurate average value. As a result the theoretical formula approach is commonly used as an aid to judgment in design rather than an absolute determination of depth and spacing. Formulas to determine depth and spacing are used more in the drainage of western irrigated lands than under humid conditions. Drains for irrigated lands are generally much deeper and the ground water flows through aquifers which are not influenced greatly by roots of plants or freezing and thawing. Hence, the conditions assumed in developing ground flow formulas are more nearly present under such conditions.

EFFECTS ON CROPS AND SOILS AS AN INDEX OF TILE DRAINAGE REQUIREMENTS

In the humid area the permeability values (hydraulic conductivity) of soils above tile depths vary greatly from season to season depending upon such factors as frost action, quantity and depth of roots and drying and cracking of soils and soil aggregations. The soil structure under such conditions varies greatly and results in variations in permeability. Under such conditions the spacing of drains is generally established by what may be termed drainage field trial studies. In Midwestern areas the effects of drains on crops of corn are observed. When drains are spaced too far apart there is a noticeable lag in plant growth in the center area between two tile drains. The tiles are therefore spaced more closely together on the next installation until a uniform cropping pattern can be obtained throughout the field. Crop yields for various depths and spacing of tile have been computed.

When drains are too far apart the fields dry unevenly after rains and areas away from the tile remain wet too long. These wet areas are readily identified by the farmer in cultivating his crops. Such observations also aid in establishing proper depth and spacing criteria. On many soils the effects of tile on draw down of the water table are observed by installing ground water observation wells. The combined results of these kinds of observations have enabled

the establishment of recommendations for depth and spacing which generally produce good results.

SOIL CONSERVATION SERVICE TECHNICAL HANDBOOKS AND DRAINAGE GUIDES

One of the principal activities of drainage engineers in SCS is to develop standards, criteria and handbook material. During the last two years the SCS has issued several chapters of the National Engineering Handbook covering Agricultural Drainage Subjects. These drainage chapters are for in-Service use but may be consulted at SCS field offices. Included among these chapters is one covering open ditches which includes design procedures for open drainage ditches. Also, chapters on drainage surveys, investigations and reports and subsurface drainage of western irrigated lands have been issued. The chapters covering tile drainage in the humid area and tile systems and appurtenances are also available. After these chapters have been in use for a few years, it is planned to make them available to the public through the Government Printing Office. The state offices of SCS have issued state engineering handbooks for work unit staffs. They include chapters on drainage and provide criteria for planning most drainage systems.

Most states having extensive drainage activities have completed or are preparing drainage guides. Drainage guides represent a fairly recent concept in compiling and making available information on drainage design standards and criteria applicable to a specific area. National and state handbooks cover general procedures applicable to a wide variety of drainage conditions and installations.

Drainage guides set forth the detailed local design requirements for drainage systems within certain geographical areas, each with its particular combinations of climate, soils, and land use. These guides represent the best accumulated record of drainage experience of farmers, ranchers, and technicians. They cover such requirements as water table control, drainage coefficients, depth and spacing of drains, and requirements for investigation, layout, and construction. Drainage guides constitute the Soil Conservation Service standards of drainage engineering in the local areas. They are established within the general criteria in the National and State Engineering Handbooks and other standards.

INVESTIGATIONS FOR TILE SYSTEMS IN HUMID AREAS

In the humid area, investigations for tile drainage systems may consist only of an on-site examination or such investigations may require extensive surveys, soil borings, and water table studies. Under many conditions, the experienced technician may install complex systems with a minimum of surveys and investigations. The experienced drainage engineer will obtain all the necessary facts but will make instrument surveys only where required. His procedure is likely to follow the following outline:

I. Need and Feasibility of Installing a Tile Drainage System
   A. Indications of high water table, or seepage
      1. Soils examination
      2. Soil auger borings
      3. Plant indicators
      4. Crop yields
      5. Hazards of cultivation
      6. Farmer experience
   B. Will increases in crop yields and other benefits increase returns sufficiently to pay costs?
      1. Crop yields before and after tiling
      2. Comparisons with similar soil, topography, and crop situations
      3. Other farm benefits
      4. Approximate costs of necessary drainage systems

II. Planning Drainage System
   A. Adequacy of outlet
   B. Determine fall available, using engineer's level
   C. Location of mains, depth and size (usually requires a profile)
   D. Depth, spacing, and size of laterals
   E. Tile lines to intercept seepage (based on soil borings)
   F. Structures and special construction items
   G. Special requirements due to acid, alkali, depth, grade, sand, or rock
   H. Cost of system.

INVESTIGATIONS WESTERN IRRIGATED AREAS

In the western irrigated area the subsurface drainage investigations are more intensive. In addition to the general type investigations previously listed, the drainage investigations for irrigated lands generally include the following: (a) Topography; (b) Soil-profile investigations; (c) Hydraulic conductivity measurements; (d) Ground-water investigations; (e) Observation wells; and (f) Piezometers. It is generally necessary to obtain or prepare a topographic map of all or part of the area to be drained.

The most detailed drainage investigations are required in the western irrigated regions where saline and alkali salts are present. The drainage engineer needs to recognize the salt problem and ordinarily he requests assistance of a soils technician to study the salt concentrations and chemical amendments which are needed. The reclamation of saline and alkali soils is outside the scope of this paper. However, the installation of subsurface drainage is usually the first step in reclamation of such salty soils where reclamation is feasible. Generally, the reclamation may require one or more of the following:

1. Drainage
2. Soil amendments such as gypsum
3. Leaching by impounding water on the area
4. Selection of adapted crops

Excellent information on the reclamation of saline and alkali soils is available in the handbook on the subject prepared by the U. S. Salinity Laboratory.[5]

SOIL-PROFILE INVESTIGATIONS

In subsurface drainage work, the texture and permeability of subsurface materials need to be determined generally to depths of 10 ft to 20 ft or more, particularly in deep alluvial sediments and where artesian pressures may exist. The success or failure of a subsurface drain depends on how well it has been located with regard to permeable layers. Exploratory borings must be made to supplement the usual conservation soil-survey information so as to obtain more detailed data especially below the 5-ft depth.

The location and spacing of exploratory subsurface borings must be based largely on a knowledge of soils, local geology, and experience gained in a particular work area. Borings must be spaced close enough to permit the location and correlation of subsurface strata as they pertain to drainage. In alluvium where sediments are heterogeneous materials deposited in a complex pattern, the spacing of borings may be 200 ft or less, and in homogeneous residual soils, a spacing of 500 ft to 1,000 ft or more may be satisfactory. In practical field application the usual procedure is to select a grid spacing based on previous experience; start subsurface explorations and attempt to correlate the data from the various borings progressively. If the correlation between borings is poor or lacking, the original grid spacing may need to be reduced and the correlation process repeated. It often develops that in certain parts of an area correlation may be good, whereas in other sections, it may be poor. In this latter case the grid pattern should be supplemented with additional borings to the extent that the subsoil and substrata configuration is made clear.

Borings on large areas should be located on a grid pattern, usually rectangular. The lines of borings may be oriented in any convenient direction to fit the area, but it is preferable to have one axis of the grid orientated fairly closely to the general direction of groundwater movement. When the spacing and grid pattern have been established, guide stakes can be placed at field boundaries and interior stakes can be sighted in. If a topographic survey is to be made, the locations of borings can be tied in on this survey.

The depth of borings should be at least 1-1/2 times the drain depth. Under average conditions in irrigated areas a 10-ft depth is considered adequate. A few deeper borings, 15 ft to 20 ft, interspersed with the others, should be made to determine the composition of underlying strata.

Fig. 2 shows a chart for recording soil borings for drainage investigations. It is especially important to determine the depth and thickness of the most permeable aquifers in order that drains may be installed at the most effective depth. On this chart are recorded the estimates of permeability which are made in the field. Even though such estimates may not have a high degree of accuracy, they indicate the relative permeability of various soil layers which is of primary importance in planning drains.

HYDRAULIC CONDUCTIVITY

The terms "hydraulic conductivity," "permeability," and "coefficient of permeability," although having different technical meanings, are quite often used

[5] "Diagnosis and Improvement of Saline and Alkali Soils," by Salinity Lab. Staff, Agric. Handbook No. 60. U. S. Govt. Printing Office.

in the same sense. The "coefficient of permeability" has been defined[6] as the rate of flow of water through a unit cross-sectional area under a unit head during a unit period of time. The term "hydraulic conductivity" is defined[7] as the coefficient k in Darcy's law $v = k\,i$, in which v is the velocity of seepage and i is the hydraulic gradient. Values of k depend on properties of the fluid, as well as on the porous medium, and reflect any interactions of the fluid with the porous medium such as swelling of soil. The term "permeability" is used in a general sense to indicate the ability of soils to transmit water. In this paper the term "hydraulic conductivity" is used in the specific sense to mean the rate of transmissibility of water through soil in cu in. per sq in. per hr, and usually abbreviated "in. per hr," assuming a hydraulic gradient of unity.

In the past much research work has been done on developing various methods and techniques for determining the permeability of soils. In general, these methods and techniques fall into two types depending on whether the soil was tested "in place" or whether soil samples were transported to the laboratory for testing. Tests made "in place" are generally considered superior for drainage investigations as it is almost impossible to obtain samples and transport them to the laboratory without disturbing them and altering their permeability.

Laboratory tests may be made in either of two ways. An undisturbed core may be obtained with a special core sampler or a disturbed sample may be obtained and taken to the laboratory where it will be dried, reduced to granule size, and then packed into a permeameter tube for testing.

Laboratory-testing methods involve placing soil samples in permeameters where they are subjected to a head of water for a designated period of time. By measuring the amount of water that passes through the sample in a given period of time the hydraulic conductivity is determined.

The method of in-place measurement of hydraulic conductivity most commonly used by the SCS was described by D. Kirkham.[8] This method involves the establishment of test holes usually 4 in. or less in diameter to a depth below the water table. The hole is pumped to a level below the static water level, and the rate at which the water in the hole returns to the original level is measured. The rate of return is a function of and enables computing the hydraulic conductivity.

Two methods of making the tests are used. These are the auger hole method and the piezometer method. Both methods are recommended for use in the SCS.

1. The auger-hole method may utilize holes dug in conjunction with the soil profile investigations. Special holes may be augered for the purpose. The hole is pumped or bailed out several times to flush any puddled-over pores along the wall of the cavity. The water level in the auger hole is allowed to become static following the cleaning process.

To make the test the water level is lowered in the auger hole with a pump or bail bucket. The distance the water level is lowered will depend upon the stability of the soil formation. Where sloughing and caving is a problem a smaller drawdown should be used and a liner of well screen or perforated pipe may be used.

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6 "Drainage Investigation Methods for Irrigated Areas in Western United States," by W. W. Donnan and G. B. Bradshaw, USDA Tech. Bulletin 1065, 1952.

7 "Measurement of the Hydraulic Conductivity of Soil in Place," by D. Kirkham, Journal Paper No. J-2505, Iowa Agric. Experiment Sta.

8 D. Kirkham, Amer. Soc. of Testing Materials, Special Tech. Bulletin 163, 1955.

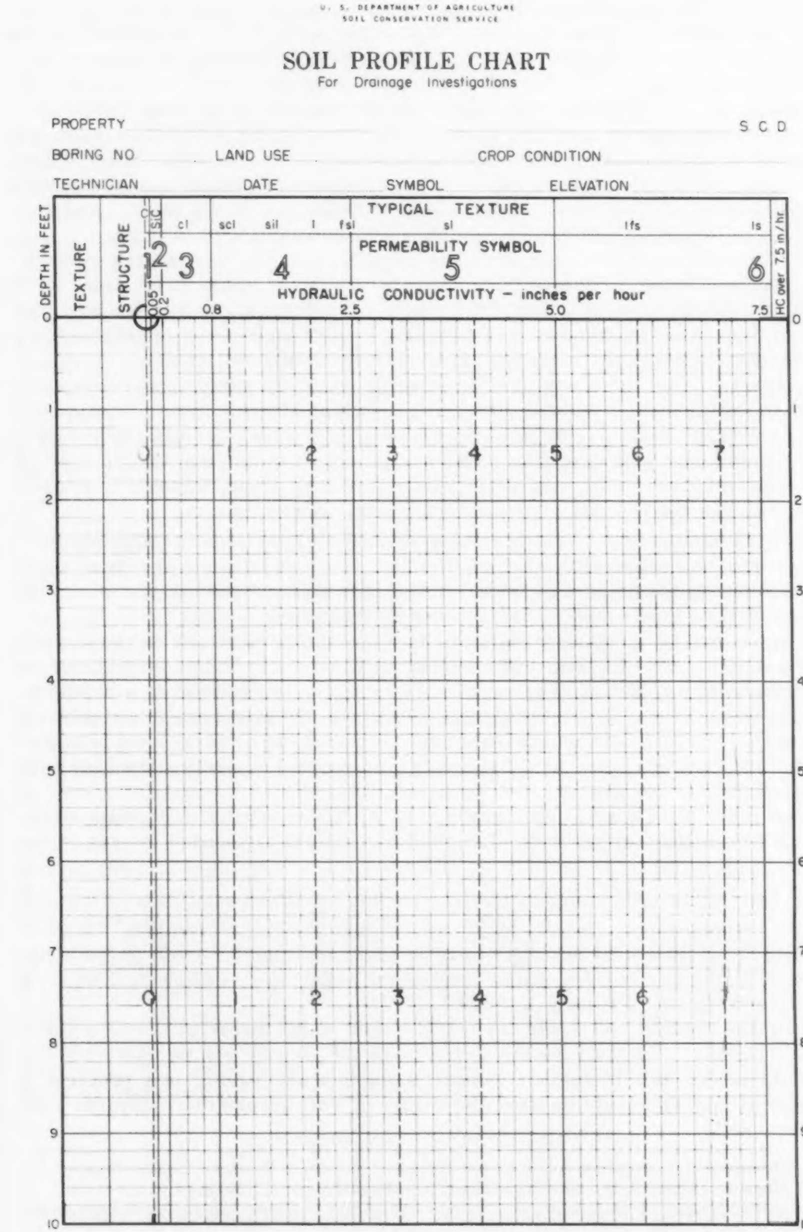


FIG. 2.—SOIL PROFILE CHART

INSTRUCTIONS

1. Make notations of texture, structure in columns at left. Note other conditions, such as wetness, sand stringers, on chart opposite depth.
2. Estimate hydraulic conductivity of each layer, considering texture, structure, pH. See instructions below.
3. Plot permeagraph on chart.
4. If hydraulic conductivity exceeds 7.5 in./hr., record at right margin.

TEXTURE LEGEND		STRUCTURE LEGEND
Clay ---- c	Loam ---- l	Massive ---- m
Silty clay ---- sic	Fine sandy loam ---- fsl	Platy ---- pl
Sandy clay ---- sc	Sandy loam ---- sl	Prismatic ---- pr
Silty clay loam ---- sicl	Loamy fine sand ---- lfs	Blocky ---- bk
Clay loam ---- cl	Loamy sand ---- ls	Grandular ---- gr
Sandy clay loam ---- scl	Sand ---- s	Single grain ---- sg
Silt ---- si	Coarse sand ---- cos	
Silt loam ---- sil	Gravel ---- gr	

ADJUSTMENTS IN HYDRAULIC CONDUCTIVITY ESTIMATES FOR INFLUENCE OF STRUCTURE AND pH

It is generally accepted practice to classify soils with respect to texture and then to adjust the hydraulic conductivity, "HC" estimates with respect to soil structure, alkali and other influencing factors. Soil texture refers to the relative proportions of the various size groups of individual soil grains in a mass of soil. Structure refers to the condition of the soil grains, (clay, silt, sand, etc.), in the way they are arranged and bound together into aggregates with definite shape.

Aggregate length and thickness has an effect upon the "HC". The overlap of aggregates having a horiz. axes 3 or 4 times longer than the vertical can have a marked effect upon "HC". The "HC" of stratum can be changed by cracks, crevices and fractures. Some fractured, (block structured), clay or shale stratum are often much higher than sands or gravel stratum. The "HC" of sandy stratum are generally higher when the grains are round and about the same size than when they are irregular in shape and of different sizes. Flat grains tend to overlap and reduce "HC" rates. The matrix rather than the coarser material in a gravel or cobble stratum govern the "HC" and should be used as a basis in estimating the "HC".

The following two tables are suggested as a possible guide in rating the "HC" of various stratum during a drainage soil survey. It is not anticipated that these tables will replace laboratory analysis and actual field "HC" measurements but that they will be used as estimates and bolstered or revised as additional experience and data becomes available.

PERMEABILITY SYMBOL RANGE for TEXTURE-STRUCTURE CORRELATION

STRUCTURE / TEXTURE	MASSIVE	PLATY	PRISMATIC	BLOCKY	GRANULAR	SINGLE GRAIN
	PERMEABILITY SYMBOL RANGE					
CLAY	1	1 – 3	1 – 2	1 – 6	2 – 5	
SILTY CLAY LOAM	2	1 – 3	1 – 3	2 – 5	2 – 5	
CLAY LOAM	2 – 3	2 – 3	2 – 3	2 – 5	3 – 5	
SILT LOAM	3	3	2 – 3	2 – 4	3 – 4	
LOAM	3 – 4	2 – 4	3 – 4	4 – 5	4 – 5	
SANDY LOAM		3 – 4	4	4 – 5	4 – 6	4
LOAMY FINE SAND				4 – 5	5 – 6	5
SAND						6
COARSE SAND						7

ESTIMATE of ALKALI INFLUENCE on HYDRAULIC CONDUCTIVITY by pH COLOR INDICATORS

SOIL TEXTURE	pH ESTIMATES FROM COLOR INDICATORS			
	8 6	9 0	9 6	10 0
	HC REDUCED (%)	HC REDUCED (%)	HC REDUCED (%)	HC REDUCED (%)
CLAY	20	40	70	90
SILTY CLAY LOAM	15	30	60	80
CLAY LOAM	15	25	50	70
SILT LOAM	15	25	50	70
LOAM	10	20	40	50
SANDY LOAM	5	15	35	45
LOAMY FINE SAND	5	15	30	40
SAND	5	10	25	40

2. The piezometer method is similar in principle except a watertight pipe is installed with a small cavity below the bottom of the pipe. The hydraulic conductivity is measured from the cavity area.

Typical field charts used for permeability measurements made by the auger hole and piezometer methods are shown in Figs. 3 and 4. The procedures are explained on the charts.

GROUNDWATER INVESTIGATIONS

The purpose of a groundwater investigation is to provide the essential information on the position and fluctuation of the water table at various points in the problem area. This indicates the extent and severity of the drainage problem over the area and provides information for selecting the general type and location of subsurface drains. Information on the position and fluctuation of the water table is obtained by establishing observation wells and piezometers as needed. Artesian pressures and water-flow should be investigated.

Observation Wells.—Observation wells are open holes placed at selected points throughout the wet area so that water-table levels may be observed. They may be cased or uncased holes depending on the stability of the soil. These wells should be established on a rectangular grid pattern and spaced so that they will give a representative picture of the configuration of the water-table surface. A portion or all of the holes made for soil borings should be cased and used as observation wells.

Piezometers.—The piezometer is a very useful tool in determining groundwater pressures and direction of flow. There is a basic difference between a piezometer and an observation well. The piezometer is a small diameter pipe which is watertight except for its open ends. It is driven to the required depth so that there is no leakage around the pipe and all entrance of water into the pipe is through the open bottom. Observation wells are open holes or of perforated pipe so the entrance of water into the well is through the entire area penetrated below the water table level. The piezometer indicates the hydrostatic pressure of groundwater at the lower end of the open piezometer tube. The observation well reflects a composite of all groundwater pressure to the depth of the well.

The piezometer is valuable in detecting artesian pressures and differences in pressure as between various strata. Groundwater moves from a point of high hydrostatic pressure to one of low pressure; therefore, the movement or flow of groundwater can be determined if the various hydrostatic pressures are known. Piezometers set close together at different depths are used to detect the vertical movement of groundwater. Piezometers spaced at horizontal intervals can be used to detect direction of horizontal seepage or movement. This technique with various ramifications is especially valuable in studying groundwater movement adjacent to canals, drains, and from higher lands.

PUMPING TEXTS

Where substantial artesian pressures are observed, additional deeper investigations are needed to locate the aquifer contributing the upward seepage. Borings as deep as 50 ft to 100 ft or more may be needed. The feasibility of pumping from aquifers under pressure may be determined by pumping tests

where initial studies indicate that pumping from wells may contribute toward solving the drainage problem.

ANALYSIS OF DATA

After data are collected the analysis include the following:

1. Water table contour maps. A contour map is used to plot the elevations of the water table at a specific date. The water table contours indicate the direction of flow and head potentials.
2. Depth of water table map. Based on the information which is developed by the water table contour map the depths to water table are shown on another map. This indicates areas with dangerously high water table.
3. Observations well hydrographs. The water table elevations are shown plotted against time. The seasonal fluctuations for critical wells are helpful for determining the source of groundwater.
4. Profile flow patterns for groundwater. These data are plotted on profile paper showing soil layers, groundwater, and hydraulic conductivity. Profile flow patterns are helpful in detecting artesian conditions, seepage from irrigation canals and other sources of underground flow.

Fig. 5 shows the working map completed with water table problems due to canal seepage. These data were obtained by investigations previously described.

DESIGN CRITERIA

The design of the system is established through the investigations described. Drains are located to provide the most effective subsurface drainage. Interceptor drains are used where feasible. Such drains may lower the groundwater from 1/4 to 1/2 mile below the drain. The theory of interceptor drainage has been explained by J. Keller and A. R. Robinson.[9]

In addition to SCS handbooks, previously mentioned, the design, installation, and maintenance of tile drainage systems are covered in publications of federal and state agencies which are available,[10,11,12] and in textbooks published commercially.

The following discussion is limited to some recent developments in the field.

QUALITY OF TILE

The tile must be of satisfactory quality to meet requirements of the site. Many failures of tile have occurred as a result of (1) freezing and thawing; (2) earth pressures; (3) action of sulfates and acids on concrete tiles; and (4) filling with sediment because of irregularities in the tile or inadequate filter. To prevent such failures, tile which have adequate strength, density, or

9 "Laboratory Research on Interceptor Drains," by Jack Keller and A. R. Robinson, Proceedings, ASCE, Vol. 85, No. IR 3, September, 1959.

10 "Farm Drainage," by Lewis A. Jones, U. S. Dept. of Agric., Farmers Bulletin 2046, October, 1952.

11 "Water," U. S. Dept. of Agric., Yearbook of Agric., 1955.

12 "Drainage Investigation Methods for Irrigated Areas in Western United States," by W. W. Donnan and G. B. Bradshaw, U. S. Dept. of Agric., Tech. Bulletin 1065, September, 1952.

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

FIELD HYDRAULIC CONDUCTIVITY TEST
AUGER HOLE METHOD
FOR DRAINAGE INVESTIGATIONS

Log No. A - 6

Estimated "HC" 2.0 in./hr. Calculated "HC" 2.36 in./hr.

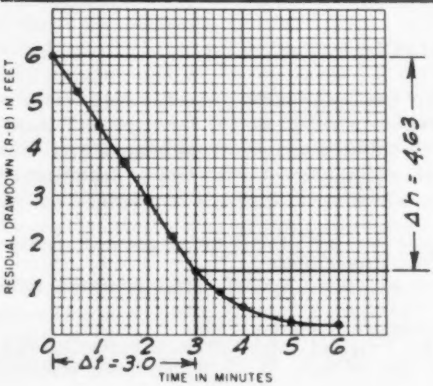
Location A.B. Doe Date 3-1-55 Technician R.B. Roe

Auger Dia. 4.0 in. Depth Hole 10.0 ft.

Sloughing slight Times Cleaned 2

pH (Soil 8.0 Water 8.1) Salinity (Soil $2\text{-}8 \times 10^{-3}$ Water 250×10^{-6})

TIME	ELAPSED TIME	Δt	DISTANCE TO WATER SURFACE FROM REFERENCE POINT: BEFORE PUMPING	AFTER PUMPING	DURING RECHARGING	Δh	RESIDUAL DRAWDOWN
			B	A	R	A-R	R-B
	Minutes	Minutes	Feet	Feet	Feet	Feet	Feet
			2.00				
10:030	0.0			8.00			6.00
:035	0.5				7.25		5.25
:040	1.0				6.50		4.50
:045	1.5				5.65		3.65
:050	2.0				4.87		2.87
:055	2.5				4.12		2.12
:060	3.0	3.0			3.37	4.63	1.37
:065	3.5				2.87		0.87
:070	4.0				2.62		0.62
:080	5.0				2.37		0.37
:090	6.0				2.25		0.25



COMMENTS

Auger hole to be used as a well. Downspout put in for casing.

FIG. 3.—EXAMPLE OF FIELD SHEET FOR MAKING HYDRAULIC

FIELD HYDRAULIC CONDUCTIVITY TEST
AUGER HOLE METHOD

A knowledge of in place soil permeability is very important in drainage design. Permeability is essential in the design of grids as well as interception drains.

The auger hole method described below is a relatively simple test that can be made with a minimum of equipment and in conjunction with the soil profile investigation. The term hydraulic conductivity is a permeability figure dependent on properties of the groundwater, as well as the soil profile.

The drainage soil profile log holes are used for the permeability tests or a special hole can be augered for the purpose. The hole is pumped or bailed out several times to permit any puddled-over pores along the wall of the cavity to be flushed out by the inseeping groundwater. This flushing process can be accomplished with a pitcher pump or a bail bucket slightly smaller than the auger hole. The water level in the auger hole is allowed to become static following the cleaning process.

TEST: The water level is lowered in the auger hole with the pump or bail bucket. The distance the water level is lowered will be dependent upon the caving and sloughing tendency of the profile. Where sloughing is a problem a smaller drawdown should be used and possibly a liner or screen will be required. The water levels and times of observation are recorded on the form. This time and distance of rise is used in the following Kirkham auger hole formula to calculate the hydraulic conductivity. The depth of water in the auger hole (D-B) should be about 5 to 10 times as deep as the diameter (2r) of the auger hole.

$$HC = 444 \times \frac{r}{Sd} \times \frac{\Delta h}{\Delta t}$$

HC - Hydraulic conductivity in inches per hour
r - Radius of auger hole in feet
S - Function from figure on this page
d - Depth of water in auger hole in feet (D-B)
Δh - Raise of water level in feet in Δt timed interval (A-R)
Δt - Time required to give Δh in minutes
h - Average depth of water in auger hole during test (D-A + Δh/2)

$r = 0.166$

$d = 8.0$ $\quad HC = 444 \times \dfrac{0.166}{6.0 \times 8.0} \times \dfrac{4.63}{3.0}$

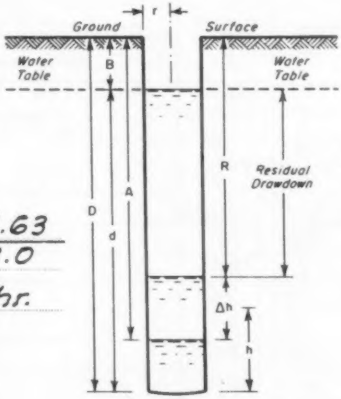
$h = 4.31$

$\Delta h = 4.63$ $\quad HC = 2.36$ in./hr.

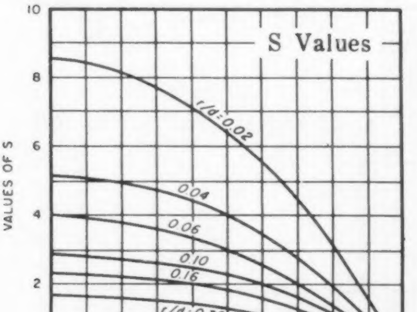
$\Delta t = 3.0$

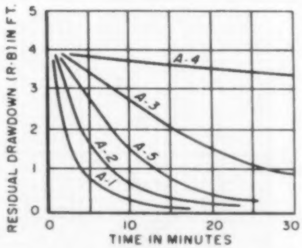
$r/d = 0.166/8.0 = 0.02$

$h/d = 4.31/8.0 = 0.54$ $\quad S = 6.0$



Auger Hole Profile





An estimate of the relative hydraulic conductivity between auger holes can be determined by plotting the residual drawdown at various recharge times. The slope of the curve gives an indication of hydraulic conductivity. The steeper the curve the higher the conductivity.

CONDUCTIVITY TEST BY THE AUGER HOLE METHOD

U S DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

FIELD HYDRAULIC CONDUCTIVITY TEST
PIEZOMETER METHOD
FOR DRAINAGE INVESTIGATIONS

Piezometer Number B-7

Estimated "HC" 0.20 in./hr. Calculated "HC" 0.32 in./hr.

Location A. B. Doe Date 6-1-55 Technician R. B. Roe

Stratum Thickness 2.0 ft. Texture silt Structure bk.

Depth Piez. 4.2 ft. Auger Dia. 1 3/16 in. Piez. Dia. 1 1/4 in.

Length Cavity 4.0 in. Sloughing None Times Cleaned 3

pH (Soil 8.0 Water 8.1) Salinity (Soil 2 x 10-3 Water 250 x 10-6)

TIME	ELAPSED TIME	Δt	DISTANCE TO WATER SURFACE FROM REFERENCE POINT			Δh	RESIDUAL DRAWDOWN
			BEFORE PUMPING	AFTER PUMPING	DURING RECHARGING		
			B	A	R	A-R	R-B
	Minutes	Minutes	Feet	Feet	Feet	Feet	Feet
			2.00				
11:01	0			4.05			2.05
:06	5				3.70		1.70
:11	10				3.35		1.35
:16	15				3.00		1.00
:21	20	20			2.63	1.42	0.63
:26	25				2.35		0.35
:31	30				2.23		0.23
:36	35				2.15		0.15
:41	40				2.10		0.10

COMMENTS

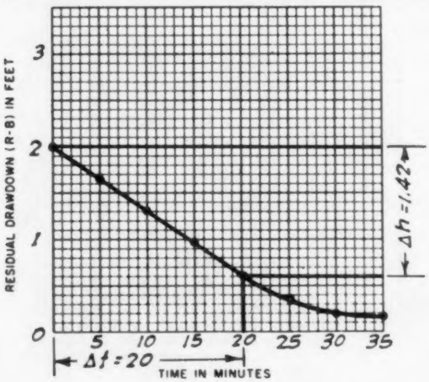


FIG. 4.—EXAMPLE OF FIELD SHEET FOR MAKING HYDRAULIC

FIELD HYDRAULIC CONDUCTIVITY TEST
PIEZOMETER METHOD

The piezometer method is used to obtain the hydraulic conductivity of a given strata or area in a soil profile. (Hyd. cond. is a permeability figure dependent on properties of the groundwater as well as the soil profile.) This is possible because the hole which is bored into the soil for the conductivity measurement is cased, except for a small cavity at its end. The rate of entry into this cavity is a measure of the hyd. cond. of the soil around the cavity.

EQUIPMENT: A 1½ to 2 inch worm auger with a square bit end is used for the test. Electrical conduit 1¼ to 2 inch inside diameter, sharpened on one end is used as the piez. The auger is ground to about 1/16 inch smaller than the inside dia. of the piez. A driving head on the piez. top prevents damage during driving. An electrical device sounding bell or blow tube can be used to measure the water level. A soil tube jack or piez removal equipment can be used to remove the piez.

METHOD: An auger hole is bored to a depth of 6 inches. The piez. is then driven into the hole about 5 inches with light blows from a maul. The hole is again augered to a depth of 6 inches below the piez. This procedure is continued until the piez. reaches the desired depth. A cavity 4 inches long is carefully augered below the end of the piez. A stop on the auger handle helps make this length precise. The auger should be removed very slowly to prevent sloughing of the cavity wall. A hollow auger or small tube to the auger bit may be required to permit air to break the suction and prevent sloughing of the cavity. The piez. is pumped or bailed out, with a pitcher pump or bail bucket, to permit the pores in the cavity wall to be flushed out. Flushing is repeated until the rate of rise in the piez. is the same as a previous pumping.

TEST: The water level is lowered in the piez. a distance dependent upon the sloughing tendency of the profile. The water levels and times of observations are recorded and used in the following Kirkham Piezometer formula to calculate the hyd. cond.

$$HC = 377 \times \frac{r^2}{c} \times \frac{\Delta h}{\Delta t} \times \frac{1}{A+R-2B}$$

HC - Hydraulic conductivity in inches per hour
r - Inside radius of piezometer in inches
c - Function from figure on this page
Δh - Raise of water level in feet in t timed interval (A-R)
Δt - Time required to give h in minutes
A - Depth to water level at start of test
R - Depth to water level at end of test
B - Depth to static water level in feet

r = 0.63

c = 12.5

Δh = 1.42

Δt = 20

A = 4.05

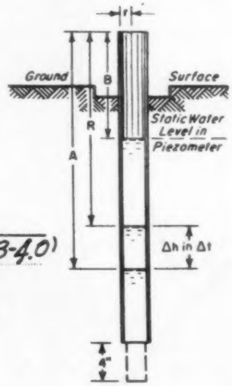
R = 2.63

B = 2.00

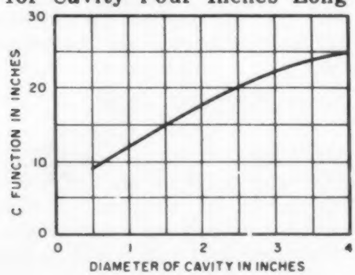
$$HC = 377 \times \frac{0.63^2}{12.5} \times \frac{1.42}{20} \times \frac{1}{(4.05+2.63-4.0)}$$

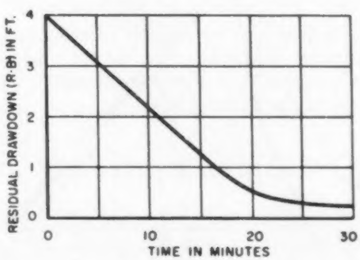
HC = 0.32 in/hr.

Piezometer Profile



C Function for Cavity Four Inches Long





An estimate of hydraulic conductivity can be determined by plotting the residual drawdown at various recharge times. The shape of the curve can also be used in evaluating characteristics of the soil strata.

CONDUCTIVITY TEST BY THE PIEZOMETER METHOD

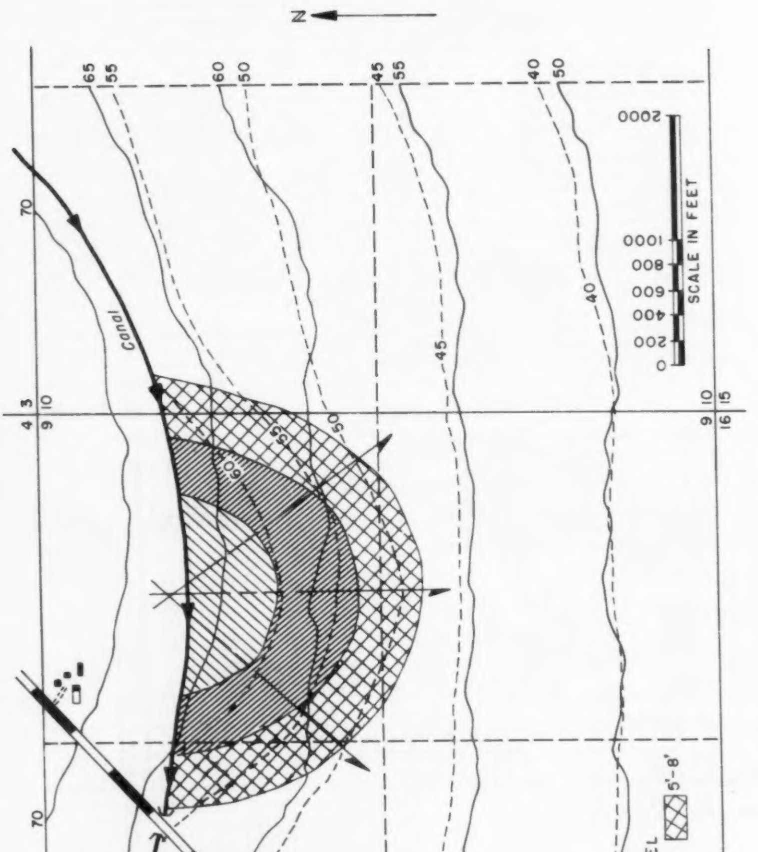


FIG. 5.—WORKING DRAWING (CANAL SEEPAGE)

uniformity in size should be used. Soils and soil water should be tested to determine sulfate content or acidity. Concrete tile should be selected based on alkali or acid conditions.

Excessive earth pressures have caused failure of clay and concrete drain tile in deep fills. Formerly, this problem could be solved in most cases by excavating a narrow trench by hand in deep cuts for the deepest portion of the cut. A wider trench would be cut by an excavating machine down to an elevation 2 or 3 ft above grade. The final cut to grade would be by hand.

The reason for this method is that loads on tile are much less in a narrow trench than in a wide trench. The high cost of labor has restricted the use of this method and, generally, it is more satisfactory to use stronger pipe which will resist the loads occurring in a wide trench excavated by a backhoe or dragline.

Frost action is especially severe on clay tile. Much damage to tile occurs by leaving tile stacked in the open over the winter. There have been many failures of clay tile in northern states due to the lines being laid at shallow depths subject to freezing and thawing.

Some concrete tile has failed because of the action of acids in soil or soil water. Failures have been more frequent in organic soils than in mineral soils. Some observations indicate that failures are more apt to occur in sandy soils than in medium and heavy textured soil.

Concrete tile has failed in the past because of action of sulfates on the tile. Such failures occurred chiefly in western irrigated lands, in southwestern Minnesota, and in a few counties in Iowa.

Satisfactory investigations to determine conditions to be met and the proper use of the ASTM specifications covering clay and concrete tile should help eliminate these causes of failure.

ASTM SPECIFICATIONS FOR CLAY DRAIN TILE

Important changes were made in ASTM C4-59T, Tentative Specifications for Clay Drain Tile, issued in November, 1959. Of greatest significance in the establishment of a new class of tile called "heavy-duty" drain tile. This class of tile is designed to provide greater strength. Table 1 shows the crushing strengths of "heavy-duty" tile as compared with the "standard" and "extra-quality" classes. The latter classes were changed only slightly from the former specifications, ASTM C4-55:

In studying Table 1 it will be noted that strengths of heavy-duty tile compared with extra quality tile have been increased more for the larger sizes than for the smaller sizes. The reason for this is that the ASTM committee established as one criteria that all sizes of the heavy duty tile should be able to withstand about the same depth of cover under projection loading conditions.

ASTM SPECIFICATIONS FOR CONCRETE DRAIN TILE

The American Society for Testing Materials issued ASTM C412-58T, Tentative Specification for Concrete Drain Tile, which has come into general use within the last year. The most significant change in this specification was the inclusion of a new class of concrete tile known as "special-quality tile." This class of tile is designed especially to resist action of acid and alkalies. The

object is to obtain a dense tile made from well graded aggregate which minimizes the leakage of water through the walls of the tile. These specifications provide for a hydrostatic test as an alternate test to a minute absorption test for special quality tile to insure a minimum of leakage through walls.

GUIDE FOR USE OF CONCRETE TILE IN ACID AND SULFATE SOILS

The Soil Conservation Service has prepared a guide for use when working with the three classes of drain tile shown in Table 2. These limits have been worked out by drainage engineers of the SCS in cooperation with P. W. Manson of the Agricultural Engineering Department, University of Minnesota. The careful application of limits shown in Table 2 will greatly improve the durability of concrete pipe installed in acid and sulfate soils.

TABLE 1.—CRUSHING STRENGTHS OF CLAY DRAIN TILE AS GIVEN IN ASTM C4-59T

Tile Size	Minimum Crushing Strength (average of five tile)		
Diameter, in in. (1)	Standard, in lb per ft (2)	Extra quality, in lb per ft (3)	Heavy duty (new class), in lb per ft (4)
4 to 6	800	1,100	1,400
8	800	1,100	1,500
10	800	1,100	1,550
12	800	1,100	1,700
15	870	1,150	1,980
18	...	1,300	2,340
21	...	1,450	2,680
24	...	1,600	3,000
30	...	2,000	3,590

BLINDING TILE AND FILTER REQUIREMENTS

Most of the tile drains in the Cornbelt States have adequate protection against rapid silting by proper blinding of drain tile with topsoil. Sod and topsoil having a high organic content make excellent blinding material to filter water which enters the tile. Contractors have generally perfected the art of blinding so that little trouble occurs and tile may be expected to have an effective life of 20 to 30 yr or more.

However, there are some areas where silting of tile lines is a serious problem. Generally, this occurs where fine sand and coarse silt particles having a low cohesion flow into the tile. Where tile is laid on a grade to produce a design velocity of about 1.5 fps or more, the velocity is high enough to wash out much of the sediment. Laying tile on grades producing such velocities is a practical solution in some locations.

Progress has been made in solving the sediment problem by design of adequate gravel or sand filters, which are widely used. If the filter material is too coarse the base material flows through the filter. If the filter material is too fine the filter impedes the movement of water into the tile. Research by several agencies has established the desirable particle size limits for gravel

filters. Frequently, pit run gravels are well graded and make an excellent filter material. Often it is desirable to mix sand or gravel from two sources to obtain a filter material having satisfactory size distribution.

Mechanical analyses of base filter material are made and gradation curves are plotted. Recommended standards adopted by the Soil Conservation Service are based on research of the Corps of Engineers, Bureau of Reclamation, and others. They are as follows:

TABLE 2.—GUIDE FOR USE OF CONCRETE TILE IN ACID AND SULFATE SOILS

(a) Acid Soils

Class of tile ASTM C412-58T[a]	Lower Permissible limits of pH values[b]	
	Organic and sandy soils	Medium and heavy-textured soils
Standard quality	6.5	6.0
Extra quality	6.0	5.5
Special quality[c]	5.5	5.0

(b) Sulfate Soils

Permissible maximum limit of sulfates (Na or Mg) singly or in combination[d]	ASTM class of tile and cement[e]
(Parts per million)	
7,000	Special quality, type V or type II cement[f]
3,000	Extra quality, type V or type II cement[f]
1,000	Standard quality, any type cement

[a] Where manufacturer or seller desires to furnish tile of a class which fails to qualify under limits shown in this table, he will be required to furnish proof that tile recommended will give satisfactory service life.

[b] Figures given represent lowest readings of pH values for soil water or soil at tile depth. Values to be confirmed by additional tests where desirable.

[c] Obtain high strength, low absorption tile where available. See Minn. Agric. Experiment Sta., Bulletin 426, "Making Durable Concrete Draintile," by P. W. Manson and D. G. Miller.

[d] Highest reading of sulfates for soil or soil water at tile depth. Values to be confirmed by additional tests where desirable.

[e] ASTM specifications C412-58T and C150-55. Where manufacturer or seller desires to furnish tile or cement of a class which fails to qualify under limits shown in this table he will be required to furnish proof that tile recommended will give satisfactory service life.

[f] Type II cement to be of high sulfate resistance. The calculated tricalcium aluminate (C_3A) compound of the cement should be less than 5.5%.

Sand or sand-gravel filters for drain conduits should be constructed of hard, durable sand or sand-gravel mixtures.

Sand or sand-gravel filter material should be selected or mixed in accordance with the gradation of the soil mass in and beneath which the conduit is to be placed. The following criteria are recommended in designing the filter:

(1) Maximum size of Material $\doteq$ 2 in.

(2) $\dfrac{D_{50}\text{ size of filter}}{D_{50}\text{ size of soil}} = 12$ to 58 (D_{50} size is that size for which 50% of the

material by weight is smaller; D_{15} is that size for which 15% by weight is smaller; etc.)

(3) $\dfrac{D_{15} \text{ size of filter}}{D_{15} \text{ size of soil}} = 12 \text{ to } 40$

(4) Not more than 5% of filter material should pass the No. 200 sieve.

(5) $\dfrac{D_{15} \text{ size of filter}}{D_{85} \text{ size of soil}} = \text{less than } 5$

(6) The gradation curve of the filter material should be approximately parallel to that of the soil.

(7) The D_{85} size of filter should be no less than 1.2 times the maximum joint spacing between drain tile or other pipe sections.

(8) Minimum thickness of filter around drain conduit should be 3 in.

In a recent publication G. Kruse[13] reports on experiments simulating radial flow into an irrigation well with the flow reversed at intervals to determine criteria for stability of uniform and non-uniform aquifers and gravel packs. The uniformity coefficient (C_u) was defined as the ratio of the D_{60} size to the D_{10} size of granular materials. The pack-aquifer (P-A) ratio was defined as the D_{50} size of the gravel pack to the D_{50} size of the aquifer. Test results indicated the following values as upper limits of the pack-aqufier ratios, if a stable filtering action was to be maintained.

Aquifer	Gravel Pack	Limiting P-A ratio
Uniform	Uniform	9.5
Non-Uniform	Uniform	13.5
Uniform	Non-Uniform	13.5
Non-Uniform	Non-Uniform	17.5

These experiments do not simulate conditions found in draintile but indicate advantages of non-uniform gradation of materials and of a low P-A ratio. They indicate the desirability of further research to determine criteria for stable filter conditions for drain tile.

Glass fiber material has found considerable use as a tile filter in recent years. This material was tested by the Agricultural Research Service at Ft. Collins, Colo. The preliminary results showed that the material will restrain particles in the coarse silt, fine sand, and larger sizes from entering the tile. The strength of the material having cross-fiber bracing is more satisfactory than that reinforced by longitudinal fibers. This material is finding increasing use.

BITUMINIZED FIBER PIPE

Also of interest is the use of other materials for drain tile. Bituminized fiber drain pipe has been used in several states for drain tile. Most installations have been of perforated pipe, 4-in. size, and lengths of 8 ft. The pipe is light and is on a competitive basis with other pipe in many areas in the Northeast, especially where the freight is an important cost factor.

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13 "Selection of Gravel Packs for Wells in Unconsolidated Aquifers," by Gordon Kruse, Colorado State Univ. Experiment Sta., Tech. Bulletin No. 66, March, 1960.

The specifications for bituminous fiber drain pipe are the current U. S. Department of Commerce Commercial Standards (CS116 - 54) modified as follows:

1. Pipe size (minimum inside diameter, in in.)	4	5	6
2. Minimum pipe wall thickness, in in.)	0.25	0.32	0.34
3. Ultimate crushing strength, in lb per ft of pipe by 3-edged bearing test	800	800	800
4. Rows of perforations (Perforations in row on 3 in. centers. Perforations shall be omitted when specified for use as conduit on steep slope.)	2	4	4
5. Diameter of perforations (+ or - 1/16 in. Standard 5/8 in. perforations may be specified for some organic soils when recommended in local drainage guides.)	5/16	5/16	5/16
6. Radial spacing of holes for two-row perforations shall be 105°. Radial spacing of holes for 4-row perforations shall be 35°, 120° and 155°, successively, from the first row.			

PLASTIC PIPE

There has been some installations of plastic drain pipe and considerable interest in the use of this material. So far installations have been few in number. The cost and service life of this material will be determined by experience and will influence the extent of its use.

PORTABLE TILE TESTING MACHINE

SCS technicians have recently used a portable testing machine to enable field tests of tile to insure that they meet specifications. A machine developed by SCS technicians weighs less than 100 lb and consists of a two-ton hydraulic jack, a ram, gage, and frame of steel beams. Light weight portable testing machines are also available commercially.

Journal of the

IRRIGATION AND DRAINAGE DIVISION

Proceedings of the American Society of Civil Engineers

IRRIGATION AND DRAINAGE POTENTIALS IN HUMID AREAS[a]

Marion Clifford Boyer,[1] F. ASCE

SYNOPSIS

In the words of the demographers, the world's population is "exploding." If present growth rates continue to the year 2000, the population of the United States will have increased approximately 1.82 times. Communist China 2.16 times, and other areas of the world by like amounts. It is estimated that by the year 2000 the United States will be producing approximately one-third more food than needed for its own people, while Communist China and much of the rest of the world will be producing less than one-half the food needed. Under those circumstances mass starvation would be inevitable. Civil engineers must accept the responsibility for making the cultivated lands yield most efficiently through proper irrigation and drainage, particularly in the humid areas of the world.

INTRODUCTION

The conquest of the bacterium and the virus has so reduced the incidence of disease throughout the world that populations long stagnant because of the tragic balance between deaths and births are suddenly increasing at prodigious rates. Unless Man soon gains control over his own fecundity, the world's population will be reduced to the simple task of toiling only to produce its own food and shelter. Food supplies in many areas of the earth have never been ample for the populations which they sustain. Should this population expansion continue starvation will reduce the multitudes. Engineers should be aware of this problem and are in position to contribute to the more efficient production of food

Note.—Discussion open until February 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 3, September, 1960.

[a] Presented at the ASCE Convention, New Orleans, La., March, 1960.

[1] Hydraulic Engineer, Indiana Flood Control and Water Resources Commission.

and fiber. They must accept the responsibility of evaluating the situation and doing whatever is within their power to alleviate it, through increased food production.

Every piece of land on the earth's surface which is capable of being cultivated may one day be called upon to yield most efficiently its share of food and fiber for Man's use and for the sustenance domestic animals. Efficient use of

TABLE 1.—POPULATIONS AND FOOD SUPPLIES OF COUNTRIES OF THE WORLD, 1937 AND 1957

Region	Land area, in sq miles	Population characteristics				Food supply, 1957, in kilo-calories	
		Total, millions per sq mile			Increase, in percentage per year	Per person	Per sq mile
		1937	1957	1957			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
United States							
Continental	3,022,387	128.9	171.2	56.8	1.43	3.10	177
Alaska	586,400	.07	.21	.4	6.88	3.50[e]	1.4
Hawaii	6,423	.40	.61	9.5	2.05	3.00[e]	28.5
Canada	3,851,116	11.34	16.59	4.3	1.92	3.14	13.5
Central and So. America							
Caribbean	1,824,338	45.87	74.18	40.7	2.41	2.50[c]	102
Argentina	1,072,748	13.49	19.87	18.6	1.95	2.98	55.5
Brazil	3,287,204	38.69	61.27	18.6	2.32	2.52	47.0
Other countries	1,540,508	19.56	28.52	18.5	1.92	2.80[c]	51.8
Soviet Union	8,649,821	170.47[a]	200.20[b]	23.2[b]	1.04	2.50[c]	58.0
Australia & New Zealand	3,078,056	8.43	11.88	3.9	1.73	3.30	12.5
Scandinavia	428,808	12.83	15.20	35.5	.83	3.10[c]	110
Central Europe	1,367,866	339.8	378.4	276	.52	2.72	750
Africa							
Egypt (United Arab Rep)	386,101	16.01	24.03	62.3	2.05	2.59	162
Union of So. Africa	472,359	9.80	14.17	30.0	1.84	2.65	79.5
Other countries	10,642,000	- -	186	17.5	2.05[c]	2.50[c]	43.8
Near East	1,523,800	57.33	79.41	52.3	1.66	2.50[c]	131
Far East							
India	1,267,094	304.3	392.4	309	1.29	1.89	584
Pakistan	364,797	66.01	84.45	232	1.24	2.00	464
Japan	142,726	70.04	90.90	637	1.32	2.07	1,310
Philippine Islands	115,600	15.44	22.69	196	1.95	1.94	380
Other countries	1,345,714	155.66	197.89	147	1.21	2.00[c]	294
Communist China	3,768,736	446.9	640.0	170	1.81	1.90[c]	323

[a] Data for the year 1939. [b] Data for the year 1956. [c] Estimated.

the soil requires that it be irrigated and drained. It is this potential for irrigation and drainage of much of the earth's surface, the humid areas in particular, which offers the greatest challenge to the civil and the agricultural engineer.

PRESENT WORLD POPULATION AND FOOD SUPPLY

Much has been written since the days of Malthus concerning the balance between the world's population and its food supply. Pessimists have decried the

fact that within a very few years starvation will be the rule. Optimists have pointed to the vast land areas not now cultivated and to the depths of the sea as sources of food which will supply Man's needs, no matter how prodigiously the human population expands. It is certain that neither view is entirely correct. A dispassionate examination of the facts concerning populations and food supplies of the nations of the world will help to clarify the picture and to show the urgent need for increasing the crop yields of the earth's soils.

Table 1 shows the present population characteristics for the major regions of the world and for the principal nations in each region. The data[2] include land area, total populations in 1937 and 1957, and food supply.

GROWTH OF THE WORLD POPULATION

One can only conjecture as to the probable growth of the world's population in future years. Several methods of estimating population growth have been suggested. The writer has chosen to use the exponential formula which, in the form of "compound interest," is given by the equation

$$P = P_0 (1 + i)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Eq. 1 has been used to determine the rates of population growth i in percentage per year for twenty years prior to 1957, utilizing data contained in Table 1, and to extrapolate forward to the year 2000.

The figures of population for 1937 and 1957 were substituted in Eq. 1 as P_0 and P, respectively, and the coefficient i determined. For the extension, the regions covered in Table 1 were combined into larger areas, Table 2, the regional coefficient i determined, and Eq. 1 again solved to extend the increase forty-three years from 1957 to the year 2000 for these larger areas. These data are given in Table 3.

INCREASE OF THE WORLD'S FOOD SUPPLY

There are many nations on the earth today whose people are continuously on the verge of starvation. As the population explosion continues, if the production of food does not keep pace, mass starvation is inevitable. If production does not expand at a greater rate, the fringe nations can never hope for that raised standard of living which is the goal of all the earth's people.

A world-wide tabulation of the estimated net food supply, in calories per day per person, available for human consumption is presented elsewhere.[3] These data have been included in Tables 1 and 2. The product of the available food supply and the population density in persons per square mile gives a figure of food supply as a measure of land yield, in calories per square mile per day (tabulated as kilocalories).

The probable food supply by the year 2000, available and required, is even more difficult to forecast than population growth. This has been attempted by

[2] Statistical Abstracts of the United States, U.S. Department of Commerce, Government Printing Office, 1956 and 1959, Section 1.

[3] Ibid., 1959, Table 1213, p. 929.

starting with an estimate of the daily requirement per person at the year 2000, based on the 1957 United States food consumption. This figure was slightly reduced for the year 2000 estimate, to compensate for the present surplus production. The per person requirement for the other regions of the World was then estimated, using the United States figure, but making it larger for the cooler regions and smaller for the warmer, in approximately the same proportion as at present.

TABLE 2.—POPULATIONS AND FOOD SUPPLIES BY REGIONS OF THE WORLD, 1957

Region	Population characteristics				Food supply, in kilocalories per day	
	Land area, in sq miles	Total, 1957, in millions	Per sq mile	Increase, percentage per year	Per person	Per sq mile
(1)	(2)	(3)	(4)	(5)	(6)	(7)
United States, Continental	3,022,387	171.2	56.8	1.43	3.10	177
Canada	3,851,116	16.59	4.3	1.92	3.14	13.5
Central & So. America	7,724,793	183.8	23.8	2.25	2.50[a]	59.5
Soviet Union	8,649,821	200.2	23.2	1.00	2.50[a]	58.0
Australia & New Zealand	3,078,056	11.88	3.9	1.73	3.30	12.9
Scandinavia & Cent. Europe	1,796,674	393.6	219	.57	2.85	625
Africa	11,500,000	224.2	19.5	2.05[a]	2.50[a]	48.8
Near East	1,523,800	79.41	52.3	1.66	2.50[a]	131
Far East	3,235,931	788.3	244	1.28	1.95[a]	476
Communist China	3,768,736	640.0	170	1.81	1.90[a]	323

[a] Estimated on basis of data for some countries in the region.

RELATION BETWEEN POPULATION GROWTH AND FOOD SUPPLY

The data contained in Tables 2 and 3 are presented graphically as bar diagrams for each region in Fig. 1. The left bar in each instance is the population in 1957 and that as estimated for the year 2000, plotted with the number per square mile as the ordinate on the land area as a base. The area of this diagram is the population volume. The right bar is the food supply, in kilocalories per square mile, over the land area as a base. On this bar the figure in parentheses is the estimated food supply available at the year 2000, the other figure is the estimated supply required in that year. If the required supply is less than that available, the difference represents a surplus. This is shown on the diagram by a dotted area. If, on the other hand, the required supply is greater than that available, the supply is deficient and the region cannot feed its people from its own crops. This deficiency is shown by the heavy-barred areas. It is evident that some regions of the world are in grave danger of soon reaching that sad state—mass starvation—foreseen one hundred sixty years ago by Malthus, because they cannot produce sufficient food for their people.

FARM LAND IN THE UNITED STATES

The United States of America, by reason of the great technological skills of its people, is an industrial giant among nations. Technological developments

in agriculture have made possible such a yield of food and fiber that the country has a great surplus each year. Many of the nations of the world would welcome this condition. That they are not so favored is due in part to the densities of their populations and in part to primitive methods of land cultivation.

The climate in the United States ranges from arid to humid and irrigation and drainage practices have been tailored to fit the climate of each region. On the arid lands of the West crops can be grown only when water is supplied by irrigation. Drainage consists in part in preventing the saturation of low spots by water escaping below the root zone of the cropped land and collecting in pockets, and in part in carrying off that part of the irrigation water which escapes beyond the cropped land by overland flow or seepage to drains.

Across the Midcontinent the climate ranges from semi-arid to sub-humid. The need for irrigation water becomes smaller and for drainage greater.

TABLE 3.—POPULATIONS AND FOOD SUPPLIES BY REGIONS OF THE WORLD, ESTIMATED FOR THE YEAR 2000

Region	Population forecasts			Food supply, in kilocalories per day per sq mile			
	Land area, in sq miles	Computed ratio 2000/1957	Total in year 2000, in millions	Per sq mile	Per person (estimated)	Required	Maximum available
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
United States, Continental	3,022,387	1.82	311	103	3.0	309	400
Canada	3,851,116	2.27	38	9.8	3.2	32	50
Central & So. America	7,724,798	2.61	478	62	2.8	174	300
Soviet Union	8,649,821	1.55	300	35	2.8	98	150
Australia & New Zealand	3,078,056	2.09	25	8	3.0	24	40
Scandinavia & Cent Europe	1,796,674	1.25	492	273	2.8	765	500
Africa	11,500,000	2.40	538	47	2.5	118	200
Near East	1,523,800	2.03	161	106	2.3	244	150
Far East	3,235,931	1.73	1,370	423	2.3	975	500
Communist China	3,768,736	2.16	1,380	366	2.5	915	400

In the South and East irrigation is used to increase the yield of crops which will produce when watered by natural precipitation alone. Drainage assumes great importance, as not only must the soil of the root zone be kept unsaturated, but storm water must rapidly be taken off the land surface as well.

For purposes of this study the continental United States has been divided into nine regions and an analysis made of the acreages farmed, irrigated, and drained in each. Data[4] are contained in Table 4.

Fig. 2 shows the selected regions, together with line diagrams showing the percentage of each framed during the years 1930, 1940, 1950, and 1954. There is a wide range in the percentage of total land area farmed throughout the United States. In 1954 it varied from 27.5% in New England to 89.7% in the Great Plains. Rocky and mountainous New England contains little land suitable

[4] Statistical Abstracts of the United States, U.S. Department of Commerce, Government Printing Office, 1956 and 1959, Sects. 23 & 24.

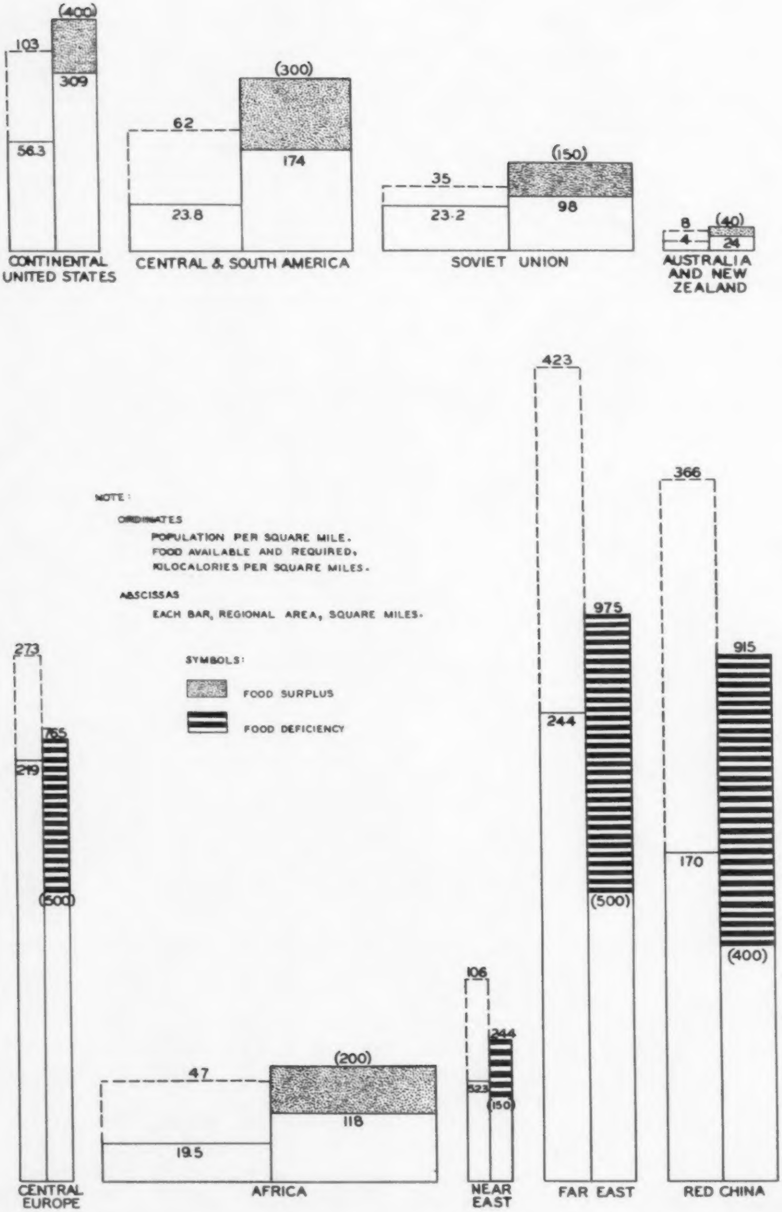

FIG. 1.—POPULATION ESTIMATES, YEARS 1957 AND 2000 AND FOOD PRODUCTION, YEAR 2000.

TABLE 4.—AREAS IRRIGATED AND DRAINED, BY REGIONS, CONTINENTAL UNITED STATES

Year (1)	Farm area, in acres (2)	Acres per farm (3)	Area irrigated, in acres (4)	Area drained, in acres (5)
(a) NEW ENGLAND (40,500,000 acres)				
1930	14,280,000	114		
1939			2,846	
1940	13,370,000	99		
1949			31,450	
1950	12,550,000	122		
1954	11,120,000	136	38,395	
(b) MIDDLE ATLANTIC (64,500,000 acres)				
1930	35,050,000	98		
1939			17,260	
1940	33,640,000	96		
1949			54,616	
1950	31,860,000	106		67,671
1954	29,900,000	116	135,886	
(c) SOUTH ATLANTIC (165,000,000 acres)				
1930	86,360,000	82		6,920,000
1939			128,037	
1940	92,560,000	83		6,810,000
1949			381,044	
1950	102,170,000	116		7,560,000
1954	98,260,000	114	536,195	
(d) EAST NORTH CENTRAL (157,000,000 acres)				
1930	110,890,000	116		33,480,000
1939			10,833	
1940	113,660,000	113		32,680,000
1949			36,237	
1950	112,100,000	126		36,020,000
1954	108,600,000	136	75,578	
(e) EAST SOUTH CENTRAL (115,000,000 acres)				
1930	72,820,000	68		4,170,000
1939			891	
1940	77,090,000	75		3,990,000
1949			6,950	
1950	79,580,000	87		4,680,000
1954	77,200,000	98	185,130	
(f) WEST NORTH CENTRAL (131,000,000 acres)				
1930	98,680,000	150		20,720,000
1939			6,286	
1940	105,490,000	157		20,240,000
1949			7,710	
1950	102,270,000	166		21,150,000
1954	100,520,000	179	44,601	
(g) WEST SOUTH CENTRAL (62,800,000 acres)				
1930	25,410,000	63		8,290,000
1939			573,381	
1940	28,040,000	76		8,810,000
1949			998,882	
1950	30,070,000	98		16,860,000
1954	29,380,000	115	1,564,557	
(h) GREAT PLAINS (408,000,000 acres)				
1930	325,310,000	282		5,980,000
1939			1,529,770	
1940	345,410,000	338		7,640,000
1949			4,291,913	
1950	363,450,000	432		9,550,000
1954	365,770,000	482	6,446,142	
(i) ROCKY MOUNTAIN AND PACIFIC (751,000,000 acres)				
1930	217,980,000	433		4,780,000
1939			15,713,626	
1940	255,590,000	503		6,200,000
1949			19,037,333	
1950	324,520,000	703		6,080,000
1954	337,430,000	797	20,959,034	

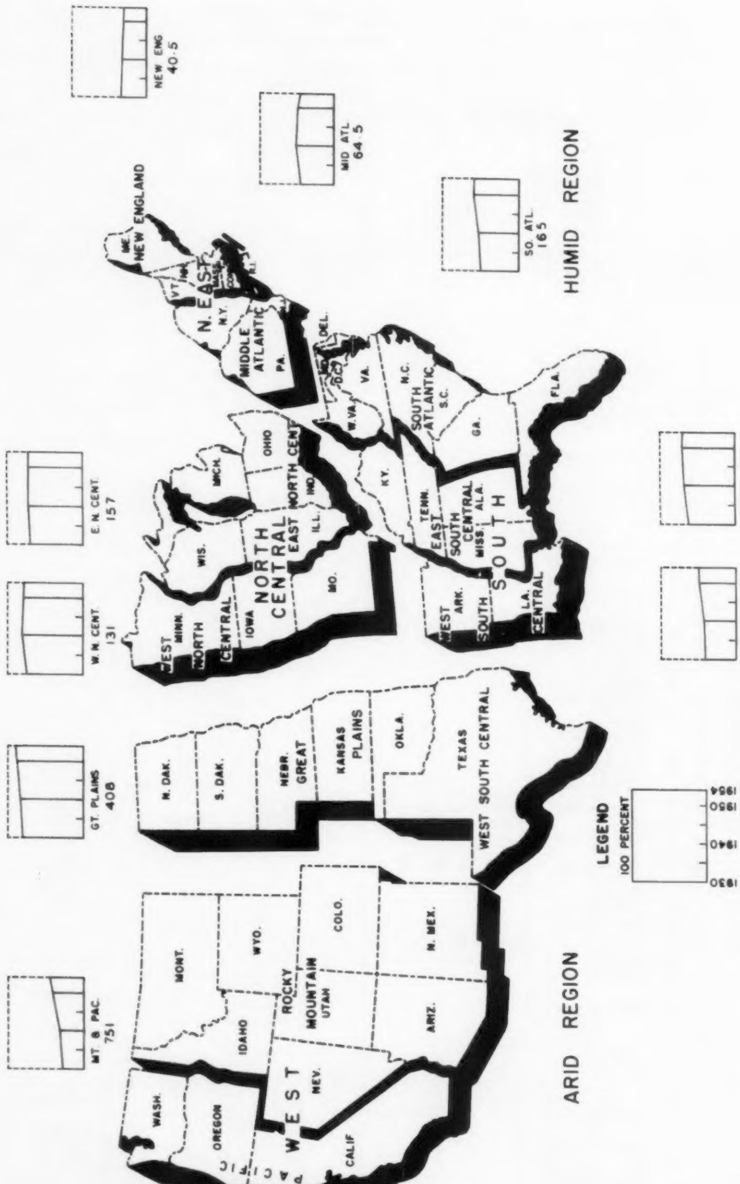

FIG. 2.–PERCENTAGE OF LAND UNDER CULTIVATION 1930-1954.

for farming, while the vast flatlands of the Great Plains may nearly all be cultivated. Nationwide, the cultivated area is 1,810,000 sq miles, a ratio to total area of 60%. Of this, the area actually harvested in 1954 was 528,000 sq miles, a ratio to cultivated area of 29% and to total area of 18%.

IRRIGATION AND DRAINAGE PRACTICES IN THE UNITED STATES

Irrigation is practiced to a greater or lesser degree throughout the United States. In the West it is the keystone of the agricultural economy. Without it few crops would be grown. In 1954, as noted in Table 4, 21,000,000 acres were irrigated in the Mountain and Pacific region, 2.80% of the total area. Across the Midcontinent crops can be grown most years without irrigation, but irrigation would increase their yield. The irrigated area in the semi-arid Great Plains was 6,450,000 acres in 1954, 1.58% of the total. In the humid East, irrigation is practiced principally to increase crop yield or, in some areas, to reduce frost damage. It is not used extensively. For example, in the South Atlantic region the irrigated area constitutes only 0.32% of the total in 1954.

Drainage is also practiced throughout the United States, but, conversely to irrigation, its need is least in the arid West and greatest in the humid East. In the Mountain and Pacific region 6,080,000 acres were drained in 1950, 0.8% of the total; in the Great Plains 9,550,000, 2.3%; and in the South Atlantic region 7,560,000 acres, 4.6%.

GROWTH OF IRRIGATION AND DRAINAGE IN HUMID AREAS

It will be noted from an examination of Table 4 that irrigation in the humid eastern United States has experienced a substantial growth during the fifteen-year period 1939-54. In each region the rate of increase has been very marked. In the semi-arid and arid western regions, where irrigation has been practiced upwards of 100 years, the rate of increase is much less.

American irrigation was born in the arid West. It is historically reported as having been first practiced by the Mormons in the Great Salt Lake Valley in 1847, though the Indians of the southwest were skilled irrigators centuries earlier. From this small beginning by a handful of emigrants has developed today's extensive irrigation practice.

The beginnings of land drainage in America are unknown, but probably were along the eastern seaboard. Its greatest growth was in the Midcontinent area, particularly in the states of Indiana, Illinois, and Iowa, and along the lower Mississippi River. While irrigation continues to grow, drainage shows comparatively little annual change, as the principal areas requiring such treatment have long since been drained.

THE NEED FOR MORE FOOD

Man faces fully as serious a problem in the control of population growth as he does in the control of the atom. The explosive results of the one could as decisively destroy civilization as would the other. Hand in hand with the control of an exploding population must go the expansion of food-producing capabilities of the earth's people through the use of all the tools and techniques of an enlightened civilization.

The greatest shortages of food occur in the Far East and China. Each will, under the circumstances assumed, fail by approximately 50% in its ability to feed its people by the year 2000.

The deficiency can be reduced only by the most intensive effort in the improvement of agriculture, but, more than that, by the development of other natural resources through the labor of a country's workers, the products of which can be traded to nations with food surpluses.

All of the foregoing estimates for the future, inaccurate though they may prove to be, still serve to emphasize the seriousness of the problem and the need for an intensive program of expanding food production by all means. This includes irrigation and drainage in the humid areas, which constitute a large part of the earth's surface, particularly in the Far East, where the nations' capabilities for feeding their people are so seriously limited.

THE FUTURE OF IRRIGATION AND DRAINAGE PRACTICES IN HUMID AREAS

The need for increased food production throughout the world will compel the development of all arable areas. The cost and difficulty of obtaining irrigation water for the remaining nonproducing arid lands have increased greatly and new developments are definitely limited, including the potentiality of desalting sea water. Humid areas, on the other hand, offer far more opportunities for yielding greater food supplies through the efficient maintenance of soil moisture in the root zone. In the midcontinent United States, for example, large areas can be brought under irrigation.

With the expansion of irrigation in humid areas in the United States will come the need for additional drainage, but not in the same proportion. Present drainage systems may, with minor modifications, be made to serve for the removal of excess irrigation water as well as storm water.

Among the other regions of the world there are vast areas within the humid climatic belts which can be brought into food production or can be more efficiently utilized. A serious problem of mineral salts deposition on irrigated lands in West Pakistan resulting from inadequate drainage has been discussed elsewhere.[5] It is estimated that 100,000 acres per yr are being taken out of production and that 1,600,000 acres need restorative treatment. Philip P. Dickinson, F. ASCE, has stated in regard to irrigation in Ceylon that because of the maldistribution of rainfall and the abnormally high demand for water by rice, the island's principal crop, irrigation is essential to the future of that nation, which experiences an annual rainfall of well in excess of 100 in. over most of its area.

THE ROLE OF THE CIVIL ENGINEER

The geoagronomist and the civil engineer share a responsibility for expansion of the world's food production. The former determines what lands may be made available and gives advice and guidance in the farming of both new lands and of lands now under cultivation. This guidance will include instruction in land preparation, farming methods, planting, and the use of fertilizers, insecticides, and fungicides.

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[5] Engineering News-Record, Vol. 163, No. 26, Dec. 24, 1959, p. 44.

By providing proper irrigation and drainage the civil engineer guarantees that water in the right amount will always be available to the plant at its root zone. It is only by this combination of scientific effort of agronomist and engineer that there can be any hope of feeding the expanding world population.

Journal of the

IRRIGATION AND DRAINAGE DIVISION

Proceedings of the American Society of Civil Engineers

DRAWDOWN DUE TO PUMPING FROM AN UNCONFINED AQUIFER

By Robert E. Glover,[1] M. ASCE, and Morton W. Bittinger[2]

SYNOPSIS

First approximation treatments of the drawdown pattern about a pumped well in an unconfined aquifer are commonly based upon the simplifying assumption that the drawdown does not alter the transmissibility of the aquifer. A second approximation is developed in this paper which accounts for the reduction of the transmissibility by the drawdown. The first approximate solution can be plotted as a single line on a graph having the dimensionless parameters $y/(Q/2) \pi K D)$ and $r/\sqrt{4 \alpha t}$ as ordinate and abscissa. The improved solution plots as a series of lines on such a graph. These lines are identified by the parameter $(Q/2 \pi K D^2)$. The method of using the graph is the same as before but it is now possible to add a family of curves indicating the ratio of the drawdown to the original depth.

INTRODUCTION

A basic assumption in the derivation of commonly used nonequilibrium well formulas is that the transmissibility remains constant with time. This assumption is met in confined aquifers if they are not dewatered. However, it is impossible to completely satisfy the assumption of constant transmissibility in unconfined situations. For such situations the transmissibility decreases as the drawdown of the water table about the well reduces the area of flow. In thick aquifers, where the drawdown is small compared to the original thickness of

Note.—Discussion open until February 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 3, September, 1960.

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the saturated material, the assumption is not seriously violated and the currently used formulas provide a good approximation of the actual conditions. But in situations where the drawdown is large compared to the original saturated thickness the present well formulas become inaccurate.

This paper develops a second approximation equation which takes into consideration the reduction in saturated thickness about a water table well. In addition, a method of refining this approximation is outlined. Like formulas already in use, the one presented here conforms to the Dupuit-Forschheimer concepts and should give valid results for computation of the free surface over that area about a well in which the slope of the water table is small.

Notation.—The letter symbols adopted for use in this paper are defined and arranged alphabetically, for convenience of reference, in the Appendix.

FIRST APPROXIMATION

The flow through a cylindrical surface of height D-y, at distance r from the well, is:

$$F = -2\pi r (D-y) K \frac{\partial y}{\partial r} \qquad (1)$$

The change in flow with respect to the radius r, is:

$$\frac{\partial F}{\partial r} = -2\pi K \frac{\partial}{\partial r}\left[(D-y)\, r \frac{\partial y}{\partial r}\right] \qquad (2)$$

Another expression for F may be written in terms of the change in storage of water beyond the radius r, with respect to time, as follows:

$$F = \int_r^\infty 2\pi r\, dr\, V \frac{\partial y}{\partial t} \qquad (3)$$

Or in terms of the change of flow with respect to the radius, Eq. 3 may be written as:

$$\frac{\partial F}{\partial r} = 2\pi r V \frac{\partial y}{\partial t} \qquad (4)$$

By combining Eqs. 2 and 4, simplifying and rearranging, the following nonlinear differential equation is obtained:

$$\alpha (D-y)\left(\frac{\partial^2 y}{\partial r^2} + \frac{1}{r}\frac{\partial y}{\partial r}\right) - \alpha\left(\frac{\partial y}{\partial r}\right)^2 = D \frac{\partial y}{\partial t} \qquad (5)$$

Because of the difficulties in solving Eq. 5, the more common development is based on the assumption that flow occurs through the entire depth (D) of the aquifer, or that y is negligible in comparison to D. Thus, starting again with Eq. 1, but neglecting y, in the sum (D-y) and following similar steps, a linear partial differential equation may be developed. This is:

$$\alpha\left(\frac{\partial^2 y}{\partial r^2} + \frac{1}{r}\frac{\partial y}{\partial r}\right) = \frac{\partial y}{\partial t} \qquad (6)$$

If the variable,

$$u = \frac{r}{\sqrt{4\,\alpha\,t}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

is substituted into Eqs. 5 and 6, they will be reduced to ordinary differential equations in y and u. In this manner, Eq. 6 may be reduced to:

$$\frac{\partial^2 y}{\partial u^2} + \left(\frac{1}{u} + 2\,u\right)\frac{\partial y}{\partial u} = 0 \quad \ldots\ldots\ldots\ldots\ldots (8)$$

If

$$p = \frac{\partial y}{\partial u} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Eq. 8 is reduced to the following first order differential equation:

$$\frac{dp}{du} + \left(\frac{1}{u} + 2\,u\right)p = 0 \quad \ldots\ldots\ldots\ldots\ldots (10)$$

An integrating factor for Eq. 10 is, $u\,e^{u^2}$, thus, giving the solution:

$$p\,u\,e^{u^2} = C_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

A particular solution, subject to the conditions that the aquifer is of infinite lateral extent, the discharge of the well is Q, and that $y = 0$ for all values of r when $t = 0$, is:

$$y = \frac{Q}{2\,\pi\,K\,D}\int_u^{\infty}\frac{e^{-\beta^2}}{\beta}\,d\beta \quad \ldots\ldots\ldots\ldots\ldots (12)$$

This is a form of the exponential integral, since,

$$\int_u^{\infty}\frac{e^{-\beta^2}}{\beta}\,d\beta = \frac{1}{2}\int_{u^2}^{\infty}\frac{e^{-\upsilon}}{\upsilon}\,d\upsilon = -\,\frac{1}{2}\mathrm{E\,i}\left(-\,u^2\right) \quad \ldots\ldots\ldots (13)$$

Values for each have been tabulated.[3, 4, 5] A well pumping formula expressed in terms of the exponential integral has been described by Thesis.[6]

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3 "Heat Conduction," by L. R. Ingersoll, O. J. Zobel, and A. C. Ingersoll, McGraw-Hill Book Co., Inc., New York, 1948. (A tabulation of the function $\int_x^{\infty}\frac{e^{-\beta^2}}{\beta}\,d\beta$ is given in Appendix F.)

4 "Tables of Functions with Formulas and Curves," by E. Jahnke and F. Emde, Dover, 1945.

5 Federal Works Agency, Work Projects Administration for the City of New York, Table of Sine, Cosine and Exponential Integrals, Vol. 1 and 2, Tables MT5 and MT6. Superintendent of Documents, Washington, D. C., 1940.

6 "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well using Ground Water Storage," by C. V. Theis, Transactions, AGU, Vol. 16, 1935, pp. 519-524.

Eq. 12 constitutes the first approximation for the unconfined situation. In developing a second approximation which takes into consideration the effect of drawdown it can be anticipated that the ratio of drawdown to the original saturated thickness (y/D) will be involved.

SECOND APPROXIMATION

An iteration procedure, based upon simple physical concepts, provides an effective means for obtaining the second and successive improved approximations. Beginning again with the basic Eqs. 1 and 3, the expressions to be used in the iteration procedure can be developed.

By rearranging Eq. 1 and substituting the variable $u = \frac{r}{\sqrt{4\,\alpha\,t}}$ it can be put in the form:

$$-2(D-y)\,\frac{\partial y}{\partial u} = \frac{F}{\pi\,K\,u} \qquad (14)$$

Integration of Eq. 14, subject to the requirement that y should approach zero as u approaches infinity yields the following expression:

$$(D-y)^2 = D^2 - \int_{u_1}^{\infty} \frac{F}{\pi\,K}\,\frac{du}{u} \qquad (15)$$

By letting

$$\sigma = \frac{Q}{2\,\pi\,K\,D^2} \qquad (16)$$

and substituting this relation into Eq. 15, an expression for y/D may be obtained in the form:

$$\frac{y}{D} = 1 - \sqrt{1 - 2\,\sigma \int_{u_1}^{\infty} \frac{F}{Q}\,\frac{du}{u}} \qquad (17a)$$

Another useful relationship can be developed by using the substitution:

$$\frac{y}{D} = \frac{\sigma\,y}{\left(\frac{Q}{2\,\pi\,K\,D}\right)} = \sigma\,\psi \qquad (17b)$$

Then Eq. 17a takes the form:

$$\psi = \frac{1}{\sigma}\left(1 - \sqrt{1 - 2\,\sigma \int_{u_1}^{\infty} \frac{F}{Q}\,\frac{du}{u}}\right) \qquad (18)$$

Similarly, substituting the variable u into Eq. 3, puts it in the form:

$$F = -\int_{u_1}^{\infty} 4\,\pi\,K\,D\,\frac{\partial y}{\partial u}\,u^2\,du \qquad (19)$$

And since

$$\psi = \frac{y}{\left(\frac{Q}{2\pi K D}\right)} = \frac{\left(\frac{y}{D}\right)}{\left(\frac{Q}{2\pi K D^2}\right)} \qquad (20)$$

Eq. 19 may be rewritten as follows:

$$\frac{F}{Q} = -2 \int_{u_1}^{\infty} u^2 \frac{\partial \psi}{\partial u} du \qquad (21)$$

These considerations yield Eqs. 18 and 21, relating ψ and F/Q to u. By alternately solving each, using values previously obtained from the other, increasingly improved values of ψ can be obtained. The integrals in Eqs. 18 and 21 are conveniently evaluated by graphical integration procedures. In working out selected values, ψ was found to converge rapidly.

TABLE 1.—COMPARISON OF THE FIRST, SECOND AND THIRD APPROXIMATIONS OF ψ WHEN $\sigma = 0.1$

u	ψ			y/D
	1st approximation	2nd approximation	3rd approximation	
(1)	(2)	(3)	(4)	(5)
0.00482	---	---	10.00	1.000
0.00500	5.01	10.00	9.16	0.916
0.00600	4.83	8.14	7.90	0.790
0.00700	4.67	7.44	7.28	0.728
0.00800	4.54	6.97	6.82	0.682
0.00900	4.42	6.60	6.46	0.646
0.01000	4.32	6.30	6.18	0.618
0.10000	2.02	2.28	2.23	0.223

An excellent starting point for the iteration procedure can be obtained by substituting a value of $\frac{\partial y}{\partial r}$ obtained from the first approximation Eq. 12 into Eq. 1 with the quantity (d - y) replaced by D. This yields

$$\frac{F}{Q} = e^{-u^2} \qquad (22)$$

A substitution of Eq. 22 into Eq. 18 then gives a second approximation for ψ of the form:

$$\psi = \frac{1}{\sigma}\left(1 - \sqrt{1 - 2\sigma \int_{u_1}^{\infty} \frac{e^{-u^2}}{u} du}\right) \qquad (23)$$

A comparison of values for the 1st, 2nd and 3rd approximation of ψ when σ = 0.1 is given in Table 1. The third approximation was obtained by graphical in-

tegration based on Eqs. 18 and 21. For most field conditions the second approximation, as computed from Eq. 23, is usually sufficiently accurate.

It will be noted that the third approximation drawdowns are slightly reduced as compared to those of the second approximation. The use of the second approximation, therefore, is somewhat on the safe side because actual drawdowns should be less than those estimated.

Fig. 1 has been plotted from Eq. 23. The lower line represents the first approximation values of ψ, whereas the other curves represent the deviation from the first approximation for several values of σ. The major deviation is found when y/D is larger than 0.5. Eq. 23 provides a simple means for constructing the large scale charts needed for every day use.

EXAMPLE

Data from a pumping test conducted near Mosca, Colorado in 1954 are used in the following example to illustrate the use of Fig. 1 to determine aquifer

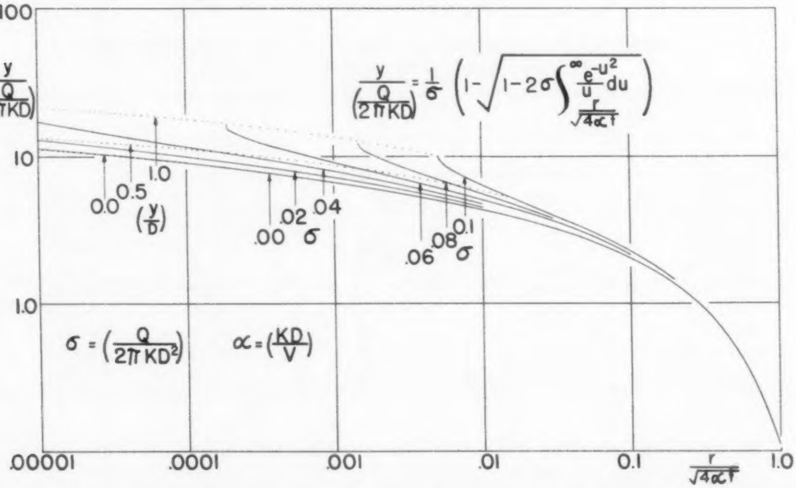

FIG. 1.—SECOND APPROXIMATION OF DOWNDRAW

characteristics. This test was previously reported by Zee, Peterson and Bock.[7] The pertinent date are Q = 167 gpm = 0.37 cfs, D = 22 ft, r = 25.8 ft and are given in Table 2.

Procedure.—Plot y versus $r/\sqrt{t}$ on transparent log graph paper of the same scale as the master chart (Fig.1). Match the resulting curve to the proper curve of the master chart for the situation of y/D = 0.14 to 0.19, then determine the point on the master chart over which an index point on the plotted graph lies. For convenience the index point y = 1.0, $(r/\sqrt{t})$ = 1.0 was chosen.

7 "Flow into a Well by Electric and Membrane Analogy," by Chang-Hung Zee, Dean F. Peterson, and Robert O. Bock, Transactions, ASCE, Vol. 122, p. 1088, 1957.

When the curves were matched, this index fell on the point

$$\frac{y}{\left(\frac{Q}{2\pi K D}\right)} = 0.77 \qquad \frac{r}{\sqrt{4\alpha t}} = 0.68$$

Thus:

$$y: 1.0 = \frac{y}{\left(\frac{Q}{2\pi K D}\right)} : 0.77$$

and

$$K = 0.00206 \text{ ft per sec}$$

This compares with values of 2.23×10^{-3} and 2.28×10^{-3} ft per sec obtained from the original analyses.

TABLE 2.—PERTINENT DATA

t, in sec (1)	y, in ft (2)	$\frac{r}{\sqrt{t}}$ (3)	y/D (4)
56,280	3.17	0.1088	0.14
70,680	3.36	0.0970	0.15
87,480	3.49	0.0872	0.16
148,680	3.91	0.0669	0.18
174,480	4.05	0.0618	0.18
232,680	4.24	0.0535	0.19

CONCLUSIONS

A second approximation treatment of the case presented by a well drawing water from an unconfined aquifer, based upon the Dupuit-Forschheimer idealization, has been obtained. This improved treatment accounts for the effect of drawdown on the areas available for the flow of ground water. The ratio of the drawdown to the original saturated thickness of the aquifer (y/D) therefore appears explicitely in the improved solution. The flow conditions are specified by a second parameter of the form $\frac{Q}{2\pi K D^2}$. This parameter is interpretable as the ratio of the well discharge Q to the flow which would pass through a cylindrical surface of height D and radius D under the action of a unit gradient. The ration $\frac{Q}{2\pi K D^2}$ therefore relates the pumping rate to a measure of the aquifer capacity. An iteration procedure is described by which the second approximation can be further refined if desired.

ADDITIONAL REFERENCES

1. Boulton, N.S. "The Drawdown of the Water-Table under Non-Steady Conditions near a pumped Well in an Unconfined Formation," Proceedings of

the Institution of Civil Engineers, V3, Pt. III. No. 2, August 1954, pp. 564-579.

APPENDIX. NOTATION

The following symbols are adopted for use in the paper and for the guidance of discussers. The dimensional characteristics are indicated in parenthesis. The terms L and T represent length and time respectively.

D = original saturated depth of the unconfined aquifer, (L);

e = 2.61828 +;

F = flow through a cylindrical surface of radius r and height (D-y), (L^3/T);

K = permeability of the aquifer, (L/T);

p = A derivative;

Q = flow of the well, here considered to be constant, (L^3/T);

r = radius drawn from the center of the well, (L);

t = time, (T);

u = $\frac{r}{\sqrt{4\,\alpha\,t}}$ (Dimensionless);

V = drainable voids in the aquifer expressed as a ratio to the gross volume, (Dimensionless);

y = drawdown of the water table caused by pumping the well, (L);

α = $\frac{K\,D}{V}$, (L^2/T);

π = 3.14159+;

σ = $\frac{Q}{2\,\pi\,K\,D^2}$; and

ψ = $\frac{y}{\frac{Q}{2\,\pi\,K\,D}}$.

Journal of the
IRRIGATION AND DRAINAGE DIVISION
Proceedings of the American Society of Civil Engineers

METHODS OF APPLYING IRRIGATION WATER[a]

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SYNOPSIS

The factors influencing the selection of a method of applying irrigation water on a farm are described in general. The various methods of irrigation and a brief discussion of the conveyance and distribution systems used for providing irrigation water on an individual farm are presented.

INTRODUCTION

Engineers are usually concerned with design and construction of larger, more complicated, and somewhat more glamorous structures than the irrigation system for an individual farm. This paper is intended to furnish the engineer with general information concerning the factors influencing the selection of a method of applying irrigation water on an individual farm. These factors are all very important and their consideration cannot be bypassed. The application of irrigation water to land may be done by a number of methods which fall into seven principal categories. Each of these methods is described and each one would be the best method under a given set of conditions. A farm may be divided into a number of fields, each of which could be irrigated by a different method from that used on other fields in the farm. A general description of the three principal methods of conveying water to the farm and to the high points of each

Note.—Discussion open until February 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 3, September, 1960.

[a] Paper presented to the Irrigation and Drainage Division, New Orleans, Louisiana, March 7-8, 1960.

[1] Proj. Mgr., Kansas River Proj., Bur. of Reclamation, McCook, Nebr.

field is given and also described are the methods used for distributing irrigation water by ditches or laterals for service to the individual field. This information is furnished so that the engineer may more intelligently advise farmers on irrigation matters.

No attempt has been made to relate consumptive use of each crop to the design of the irrigation system. It is considered that this factor has a principal influence on frequency of irrigation rather than method.

INFLUENCING FACTORS

There are five major factors which influence the selection of a method of applying irrigation water which are; (1) effective growing season rainfall; (2) intake rate and capacity for available water in soils; (3) topographic relief and soils; (4) crops to be irrigated; and (5) cost of applying water. The selection of a method of applying water will be influenced by one or a combination of these factors. There may be several different methods used by a farm operator on a single farm unit. Each method of irrigation is the best for a certain combination of factors.

Effective Growing Season Rainfall.—This factor, more than any other, is the one which lends credence to the common statement that irrigation in humid regions is different from that in the arid regions. When referred to in the humid areas, the word "irrigation" is usually preceded by the word "supplemental." In fact, there is no such practice as supplemental irrigation; however, it is readily understandable that irrigation in this instance is considered by some to supplement the rainfall. When a farm is irrigated, rainfall merely supplements the irrigation. In the more arid regions there is very little usable rainfall during the growing season, whereas in the humid regions, there are rains yielding a sufficient volume of moisture to completely replace an application of irrigation water. It is conceivable that these rains may be so spaced that optimum moisture for crop production may result without irrigation.

Contrary to common belief, the probability of occurrence of these rains dictates a larger capacity in the delivery system than would be required if there were less probability of such rains. Because of the low probability of beneficial rains in arid regions, the frequency and dates of irrigation are influenced by date of planting, type of crop, soil moisture, etc. The farmer can fairly well regulate the dates for irrigating certain crops so that a minimum capacity will be required in the system. The practice of rotating irrigation among farmers is frequently used. When this is done, each farmer is notified at the beginning of the irrigation season as to the days during the irrigation season when he will receive water for his farm.

A larger capacity in the delivery system is required when it is operated on a "demand" basis. In areas where there is a good probability of rains having an accumulation of from 1 in. to 3 in. in 48 hr the date of irrigation cannot be controlled by the farmer. After one of these rains has occurred in an area, the subsequent need for irrigation water becomes more nearly simultaneous for all farms and all crops. It is readily apparent that a "demand" system to meet all requirements at any time would dictate much greater capacity than a "rotation" system where each farmer takes his water in turn regardless of rainfall conditions.

Irrigation in the humid regions will also require greater farm conveyance system capacities for delivery of water than in arid regions, but the total volume

of water required for the irrigation season will be greater in arid regions than in the humid regions because there is only a small amount of usable rainfall to supplement the irrigation requirements in the arid regions.

Of course, the intensity of rainfall will have a marked influence on the selection of a method of applying irrigation water. A heavy rain occurring immediately following an irrigation, when the soils are already saturated, may cause serious erosion of the topsoil. The amount of such damage would be dependent upon the nature of the soils and the topography.

Intake Rate and Capacity for Available Water in Soils.—Intake rate is the rate, generally measured in inches of water per hour, at which water moves into the soil. This factor has a great influence on determining the method of applying water. If the intake rate is high, it may be virtually impossible to apply water by surface methods because the required flow of water would be exceptionally large. Conversely, if the intake rate is low, the application of irrigation water would be in such small quantities that it would be almost continuous to meet the plant requirements.

Available water in soils is the volume of water in the soil which is readily available for plant use. This is usually measured in inches of water per foot of soil depth. Generally speaking, the available water in soils is inversely proportional to the size of soil particles. This factor influences the frequency of

TABLE 1.—INTAKE RATE AND AVAILABLE WATER BY SOIL CLASS

Soil Class (1)	Intake rate, in in. per hr. (2)	Available Water, in in. per ft of depth (3)
Sands	3.0 or above	0.25 - 0.75
Loamy Soils	2.0 - 3.0	0.75 - 1.25
Sandy Loams	1.0 - 2.0	1.00 - 1.50
Fine Sandy Loams	0.5 - 1.0	1.50 - 2.00
Clay Loams	0.2 - 0.5	1.50 - 2.00
Clays	Less than 0.4	2.00 - 3.00

irrigation since soils with a large capacity for available water would need replacement of its available water less frequently than would soils with a small capacity. The capacity for available water is not only dependent upon the volume of voids to be filled by water but also depends on the size of the voids since the water is held in an available range by capillarity. A sandy soil holds little available water because of the larger voids and rapid percolation of water below the root zone of plants.

It may be observed from Table 1 that available water varies inversely as the intake rate varies.

It should be apparent from Table 1 that sandy soils would require frequent light applications of water and that clay soils would require infrequent heavy applications of water. The length of time required for each irrigation of clay soils would be much greater than for the sandy soils.

Topographic Relief and Soils.—The topographic factor has perhaps the greatest influence on the selection of a method of applying irrigation water. Topography cannot be considered alone but must be considered in relation to soils. These factors will influence the length of run, the length of time required for

each irrigation, waste of water from the field, loss of topsoil by erosion, and farm labor costs. It must be remembered that some of these items are effected by the intake rate and erodability of the soils.

The length of run is generally, where not controlled by size and shape of field, determined by the size of the irrigation stream and the intake rate. A simple rule of thumb for determining the size of irrigation stream in gpm is ten divided by the field slope in percentage. For example, if the slope of a field is 2% the irrigation stream would be 5 gpm. If the intake rate is 0.3 in per hr for clay loam (Table 1) and the row spacing is 40 in. the intake rate would be 1 gpm per 100 ft of row; Therefore, a 5 gpm irrigation stream would supply water to a row 500 ft long. At the rate of 0.3 in. per hr for clay loam, it would require about 5 hr to restore the available water to each foot depth of soil. Where the ground surface is undulating and short irrigation runs result, it might be necessary to modify the ground surface by land grading.

The danger of soil erosion is one of the greatest concerns in planning to irrigate a farm. Erosion of soils in the humid regions is more apt to be caused by heavy rainfall than by the application of irrigation water. Where soils are deep, in excess of 6 ft, the question of erosion becomes less important. Serious damage to the soil will not result from erosion of deep soils which meet all other tests of irrigability but erosion may be serious enough to require expensive curative measures for continued irrigation. The erosion problem becomes more severe as the depth of soil becomes less than 6 ft.

In considering shallow soils, the question of slope and water depth on the land surface, modified by soil texture and structure, become paramount. The writer knows of no finite method of determining the percentage of slope which can safely be cultivated without erosion by intense rainfall. For lack of a better method, an attempt is made to utilize the tractive force theory which has been applied to canal design. Tractive force (psf) is computed by the formula W (weight of water, in lb per cu ft) times D (depth of water, in ft) times S (slope, in ft/100). Limits of tractive force have been established for various soil types through research. Considering two methods of irrigation, by furrows and corrugations, Table 2 showing maximum limiting slopes was developed.

It should be emphasized that the limits of slope shown in Table 2 are for areas subject to severe storms which would result in full water depth for furrows of 4 in. and for corrugations of 2 in. and no resulting erosion. These are extreme conditions and experience has shown that use of good judgement and management should warrant irrigation of slopes at least twice as steep as the computed slope without danger of serious soil erosion by heavy rainfall.

Crops to be Irrigated.—This factor is somewhat less important than the others in selecting a method of applying irrigation water. Most crops can be grown by a number of methods of irrigation. Generally, the method used for various crops must take into consideration the need for and method of cultivation and the method of harvesting.

Certain crops such as corn, potatoes, onions, milo, dry beans, cotton, peas, sugar beets, sugar cane, etc., can be more readily cultivated and harvested when planted in rows. In these cases furrow irrigation is the most practical.

Alfalfa is harvested several times each season and does not require cultivation to control weed growth. It is usually irrigated by corrugation, border or flooding from field ditches. Small grains are also irrigated by the same methods with the corrugation method being used predominately.

Pasture irrigation differs from that of other crops in that plants have comparatively shallow root systems and small applications of water at frequent intervals are suggested. Although irrigated pasture has about the same total water requirement as alfalfa, much more frequent applications of water are required. Water moves over sod more slowly than similar land planted to alfalfa or small grains. Flooding and border methods of irrigation are the most common for pasture. Pasture on an undulating surface is occasionally irrigated by sprinklers.

Rice irrigation is widely practiced in such states as Arkansas, Louisiana, and Texas. Rice is grown in essentially the same way as other small grains except that the land on which the crop is grown is submerged for 60 to 90 days, or more, during the growing season. Because of the necessity to hold water on the surface for a long period of time, find textured soils with a very low intake rate are considered the most suitable. During much of the growing season, the water depth is maintained at about 5 in. To maintain a uniform depth, the only suitable method of irrigation is with basins.

Other crops such as orchards and vegetables may be irrigated by different methods to meet specific conditions. Other factors discussed herein influence the method more than the crop itself.

TABLE 2.—PERMISSIBLE SLOPE BY SOIL TYPE

Soil type	Tractive force, in lb per sq ft	Computed permissible slope, in percentage		Safe permissible slope, in percentage	
		Furrows	Corrugations	Furrows	Corrugations
(1)	(2)	(3)	(4)	(5)	(6)
Sand	0.025	0.12	0.24	0.25	0.50
Loamy sand	0.025	0.12	0.24	0.25	0.50
Sandy loam	0.040	0.19	0.38	0.40	0.75
Fine sandy loam	0.050	0.24	0.48	0.50	1.00
Clay loam	0.250	1.20	2.40	2.50	5.00
Clay (heavy)	0.650	3.10	6.20	6.25	12.5

Cost of Applying Water.—In selecting a method or irrigation, cost becomes an important item. Where a crop can be irrigated by one or more methods, the method selected is dependent upon the first cost and the annual cost. In many cases, the first cost may be high but the annual cost, particularly the expenditure of labor, may be lower than any other method. Of course, where only one method of irrigation can be used, such as in the case of rice, the cost of preparing the land will determine whether or not the farm will be used for rice.

The cost of land development required to utilize some certain method of irrigation is strictly a computation of the amount of excavation required to modify the topography so that the particular method may be utilized. The initial construction costs of irrigation systems may be as low as 10 dollars per acre. Although the initial costs of constructing an irrigation system may be low, the resulting efficiency of the system may also be low and the result would be a reduction in net crop returns.

METHODS OF IRRIGATION

For economical and efficient distribution of irrigation water, the operator must have complete control of the water as it flows from the head ditch onto the land. When uncontrolled streams of water are turned into fields, waste, inefficiency, and uneven distribution are almost certain to result. The most common methods of irrigation are: furrow, corrugation, border, basin, flooding, sprinkler, and subsurface irrigation. For a given set of conditions, one of these methods should be selected as the most desirable.

Furrows.—The furrow method of irrigation is most commonly used for such row crops as potatoes, corn, fruit, vegetables, cotton, sugar beets, and sugar cane. The furrows are ordinarily made during the process of cultivation. Under usual conditions, a furrow 4 in. wide and 4 in. deep is normally used while the crop is young and the furrow is made wider and shallower as the crop matures. Furrows are most commonly run directly down the slope, but sometimes can be run on the contour to control erosion from rainfall. Furrows may be run across the slope of the field to keep it rectangular for ease of cultivation and to keep the furrow lengths uniform, but care should be taken to prevent overtopping the furrows and breaking them.

TABLE 3.—SUGGESTED LENGTH OF FURROWS[a,b]

Slope, in % (1)	Loamy sands (2)	Sandy loams (3)	Silt loams (4)	Clay loams (5)
0-2	250-400	300-660	660-1320	880-1320
2-5	200-300	200-300	300-660	400-880
5-8	150-200	150-250	200-300	250-400

[a] Measured in feet.
[b] Irrigation Adviser's Guide, U. S. Dept. of the Interior, Bur. of Reclamation.

Unnecessary water loss will occur if the furrows are too long. The initial irrigation stream in each furrow should be large enough to get to the end of the furrow rapidly without excessive erosion and then should be cut back as close as practical to a stream equal to the intake rate of the furrows (Table 4). Table 3 presents some suggested lengths of run for various slopes and soil textures.

A generalized table for converting intake rate in in. per hr to gal per min per 100 ft of furrow for various furrow spacings is presented as Table 4.

A review of the "Influencing factors" previously described would lead to the conclusion that the furrow method of irrigation is the most efficient and economical for row crops. In the humid areas where heavy rains may occur during the growing season, furrows should be used down slopes where the slopes are not steep for the specific soil type. Where slopes exceed the safe permissible slope shown in Table 2, the furrows should be run across slope, or they should be run on a contour between dikes spaced to prevent heavy rain runoff from cutting across the furrows.

Corrugations.—Corrugations are shallow furrows running down the slope from head ditches and are used for irrigating close growing crops such as grain, alfalfa, or pasture. The water soaks laterally through the soil, wetting the area between the corrugations to the depth of the root zone. This method is generally used on fine textured soils that take water slowly and on land that is moderately steep or irregular. Corrugations are generally 2 in. to 3 in. deep and

are spaced from 14 in. to 36 in. apart. The streams used in corrugations may vary from 1 to 5 gpm depending on slope and soils. The length of run should be about the same as for furrows (Table 3). This is an economical and efficient method or irrigating crops which are adapted to its use. Based on Table 2, it is a highly desirable method to use on steep slopes with fine textured soils.

Borders.—The border method of irrigation consists of dividing the field into a number of strips separated by low flat dikes usually running in the direction of greatest slope, preferably at a uniform grade. The field must be level between border dikes, that is, normal to the direction of the dikes and the dikes should be constructed so as to permit farming across them, usually about 3 ft wide and 1 ft high. These strips may vary from 20 ft to 66 ft in width and from 200 ft to 1,500 ft in length, depending on the size of the available stream of water, the intake rate of the soil, and the slope of the land. The idea in border irrigation is to advance a sheet of water down the narrow strip of land, allowing the water to enter the soil as the sheet advances. Care should be taken to design the system so that the required amount of water has been delivered to the strip between the dikes by the time the leading edge of the sheet of water has reached the end of the field, thus reducing surface waste.

TABLE 4.—INTAKE RATE AND FURROW SPACING

Intake Rate, in in. per hr	Furrow spacing, in in.					
	18	24	30	36	42	48
	Intake rate, in gpm per 100 ft of furrow					
0.25	0.39	0.52	0.64	0.78	0.89	1.04
0.50	0.77	1.04	1.28	1.54	1.75	2.08
0.75	1.15	1.55	1.74	2.31	2.65	3.08
1.0	1.55	2.06	2.58	3.10	3.54	4.12
2.0	3.10	4.12	5.16	6.20	7.08	8.24
3.0	4.65	6.18	7.74	9.30	10.62	12.36

This method of irrigation is most suitable for small grains, hay, and pasture. It can be used on a wide range of soil textures but is not generally recommended for fine textured soils with a low intake rate.

Slopes in excess of 3% are undesirable. Where slopes are more than 3%, it might be desirable to run the borders across the slope and level the land in terraces between the borders. This is a fairly expensive land leveling operation but it is a one-time expenditure and when capitalized over a long period of years may prove to be the least expensive method of irrigation from the standpoint of annual cost. Three requirements for the use of the border method are relatively large streams of irrigation water, gentle topography, and careful land grading.

A general guide for the design of the width and length of border strips for various soils and sizes of irrigation streams is presented as Table 5.

Basins.—The basin method of irrigation consists of running large streams of water into level plots surrounded by dikes. This method is especially adapted to land that is nearly level and may be used on a wide variety of soil textures and crops. This method may be used on fine textured soils where, because of the low intake rate, it is necessary to hold water on the surface to secure adequate penetration. When irrigating, basins are rapidly filled with water to a depth sufficient to replace the available water in the soil (Table 1). Be-

cause of the cost involved in leveling the fields, its use is restricted to extremely flat land. It may be the cheapest and most efficient method of irrigating small, odd shaped, fields of 1 to 3 acres.

Almost any crop can be raised by this method of irrigation including pasture, orchards, hay, small grains, and many row crops, although it may restrict cultural practices. It is the only method adapted to the irrigation of rice where water is required to stand at a depth of about 5 in. for 60 to 90 days.

This method is suited to large streams of irrigation water, rapid irrigation, and a small amount of labor. In the humid areas, where heavy rains may occur at any time of the year, special care should be taken to provide adequate drainage relief for each basin.

Flooding.—The flooding method is used most generally for the irrigation of pasture. Field laterals are constructed on the contour having a grade of not more than 0.1 ft per 100 ft. Water is diverted from the field lateral and allowed to flow, uncontrolled, over the land. Field laterals are usually close enough together to collect the runoff water, before it is allowed to concentrate in a swale, and then the water thus collected in the lower lateral is redistributed

TABLE 5.—SUGGESTED WIDTH AND LENGTH OF BORDER STRIPS[a,b]

Irrigation stream, in 1,000 gpm (1)	Soil textures					
	Sandy		Silt Loam		Clay	
	Width (2)	Length (3)	Width (4)	Length (5)	Width (6)	Length (7)
0.5	20	200-300	25	330-550	30	550-770
0.5-1.0	30	330-440	35	550-770	40	660-880
1.0-2.0	35	440-550	40	550-770	50	660-1,000
2.0-3.0	40	550-660	50	660-880	60	880-1,320
3.0-4.0	66	660-770	66	880-1,320	66	1320-1,500

[a] Measured in feet.
[b] Irrigation Adviser's Guide, U. S. Dept. of the Interior, Bur. of Reclamation.

over the next lower field. This is perhaps the least expensive method of irrigation from the standpoint of first cost. To fully irrigate all of the land below the ditch will require a great deal of time and work by the irrigator. When this method is used, the farmer generally figures that less than 100% of the land will be irrigated and tends to balance the cost of labor against the crop value.

Sprinkler.—This method is the application of water to the surface of the soil as a spray, somewhat as rain. It is adapted to most soils that can be irrigated and is particularly adapted to sandy soils which take water rapidly, soils that are too shallow, too steep, or too rolling to be irrigated by other methods. Small streams of water may be used efficiently by sprinkler irrigation with little or no field runoff. It is adapted to all major farm crops except rice.

There are certain limitations to the use of sprinkler systems. Water distribution is effected by wind causing, in some cases, an unequal distribution of water when the wind is in gusts. Annual operation and maintenance costs (including power costs) are usually higher than for other methods. The water that is used must be clean and free of debris, and a constant water supply is desirable for the most economical use of the equipment.

The use of sprinkler systems for irrigation has developed rapidly in the humid area over the past few years. In this area, the production of crops is not fully dependent upon irrigation, however, during periods of drought there may be serious crop losses. Many farmers have found that it pays to have a sprinkler system which can be used in case of drought, because of the rapidity with which the system can be placed in operation when needed. All other methods of irrigation require that the farm be prepared for irrigation before crops are planted in the spring. Once this is done, the farmer should irrigate without waiting for a severe drought condition to occur.

Subsurface.—Subsurface irrigation requires complete control of the elevation of the water table so that the plant root zone in the soil is kept free from excess water but is continually supplied with capillary moisture during the growing season. Lands suitable for this method of irrigation are rather limited in extent and occur on very few farms.

Soils best adapted to this method are those that permit rapid lateral and downward movement of water yet are capable of providing moisture by capillarity from the water table throughout a major portion of the root zone. The topography should be smooth, uniform, and approximately parallel to the water table. Many crops are adapted to this method of irrigation but orchards are not usually adapted unless the method is supplemented by one of the other methods of irrigation.

When natural conditions prevail which will permit subsurface irrigation, the farmer is indeed fortunate because optimum crop production can be had with little or no expenditure of money. The largest area practicing subsurface irrigation is in southern Florida. In this area, the subsurface drainage system is also used as an irrigation system and it is possible to regulate the groundwater within a very narrow range of fluctuation even after very heavy rainfall.

DISTRIBUTION SYSTEMS

The farm distribution system should be laid out to most efficiently serve each field after the method of irrigating the field has been selected. Water is generally made available to the high point on each farm and is distributed by gravity from the point. When this is true, the distribution system should consist of a main ditch and several laterals or head ditches. The head ditches are used to provide even distribution over each field. A variation of this system would be a combination main ditch and a low pressure pipe lateral system with gates for each turnout or each furrow. The notable exception would, of course, be the high pressure pipe system which is used in connection with sprinkler irrigation. This system is often used when the water supply is either pumped directly from the stream or pumped from a well.

Open Ditch System.—The main ditch should be built to a capacity sufficient to carry all of the water available to the farm. In many of the western states, the permissible stream diversion is limited to a rate based on 1 cfs for a certain number of acres. For instance, the Nebraska law limits the diversion to 1cfs for 70 acres. Because of the coincidence of extreme drought over large areas in humid areas and the occurrence of hot dry winds, the permissible limit should be much greater in the humid areas than is generally used in arid areas. If the water supply is not a limiting factor, the main ditch should be designed to a capacity shown in Table 6.

The main ditch should, in most cases, be constructed as a permanent ditch. The capacity should be reduced as laterals are taken off of it, with the residual

capacity being determined from the area remaining below the turnout of the lateral. Laterals or head ditches can be designed on the same criteria as shown in Table 6. Ditches should be run on grades of not to exceed 0.1 ft per 100 ft with appropriate drop structures where necessary to use up excessive head. The ditches should be designed so that the water surface can be raised to 6 in. above the initial ground surface of the field to be irrigated. The main ditches should be designed with a freeboard of 1 ft and the ditch banks should be at least 2 ft wide.

Water is usually diverted from the head ditch or lateral to the furrows by using siphon tubes or spiles. The size of siphon tube is dependent upon the desired flow in the furrows. Tabel 7 shows the discharge in 2 pm for various size siphon tubes operating under different heads.

TABLE 6.—SUGGESTED DITCH CAPACITY BASED ON IRRIGABLE ACREAGE

Irrigable acres in farm (1)	Ditch capacity, in cfs (2)	Irrigable acres in farm (3)	Ditch Capacity, in cfs (4)
20 or less	1.0	90 - 120	5.0
20 - 40	2.0	120 - 160	6.0
40 - 60	3.0	160 - 200	7.0
60 - 90	4.0	200 - 240	8.0

TABLE 7.—DISCHARGE CAPACITY OF SIPHON TUBES

Tube size, in in.	Head - Inches				
	2	3	4	5	6
	Discharge, in gpm				
3/4	2	3	5	6	7
1	4	5	7	8	9
1 - 1/8	6	7	8	10	11
1 - 1/4	8	10	12	13	15
1 - 1/2	13	16	18	21	24
2	21	27	32	36	40

When the border, basin, or flooding method of irrigation is used, it may be necessary to use several siphon tubes to provide the required discharge. When permanent borders or basins are built, it is often desirable to build a permanent turnout structure in the ditch bank.

Low Pressure Pipe Lines.—A very efficient method of conveying and distributing farm irrigation water is through the use of low pressure pipe lines. This method has many advantages in that it practically eliminates evaporation and seepage losses, reduces maintenance work, improves water control, and eliminates the ditch bank weed problem. Although initial installation costs are higher than for open ditches, the overall annual costs are often less.

These systems may be permanently buried concrete pipe or they may be portable light weight metal pipe. These systems may be built in any combination of permanent buried pipe and portable pipe. Heads should not exceed 20 ft and

TABLE 8.—FACTORS INFLUENCING THE SELECTION OF A METHOD OF APPLYING IRRIGATION WATER

Method of applying irrigation water (1)	Major Influencing Factors: Effective growing season rainfall (2)	Intake rate and capacity for available water in soils (3)	Topographic relief and soils (4)	Crops to be irrigated (5)	Cost of applying water (6)
Furrow	Hazard of erosion down steep slope	Adaptable to most all soil textures	Uniform slopes of from 0.25% to 2.5%	Row crops (sugar beets, corn, cotton, vegetables, sugar cane, etc.)	Most economical when uniform slopes are not over 2.5%
Corrugations	Can be used on comparatively steep slopes and heavy rainfall	Fine textured soils with low intake	Irregular fields, short runs, and slope up to 8.0%	Close growing crops (grains, hay, and some vegetables)	Most economical in first cost. Requires moderate labor
Borders	Can distribute water rapidly. Not damaged by heavy rains	Not desirable on fine textured soils with low intake rate	Smooth uniform slopes of not over 3.0%	Small grains, hay and pasture	Economical where heavy land grading not required. Moderate labor required.
Basins	Will accommodate heavy rainfall with required drainage	Adaptable to all soil textures	Level land	Most all crops. Only method for rice.	Where heavy land leveling not required costs are moderate. Labor costs are minimum
Flooding	Heavy rainfall permissible	Coarse to medium textured soils with high intake rate	Irregular fields and topography with slopes up to 8.0%	Pasture or native hay	First cost very low. Annual labor high for 100% coverage
Sprinkler	Heavy rainfall permissible	All soils but particularly good or coarse textured soil	Undulating topography permissible with slope of no consequence	All crops except rice	First cost, annual O & M and labor costs are high
Subsurface	Rainfall no item with controlled subsurface drainage	Loam or sandy loam soils with good lateral movement of water	Surface should be smooth and parallel to water table	Most all crops except orchards and rice	Minimum first cost and minimum labor cost

it is preferable to keep the head below 8 ft. Since the pipe line has a fixed capacity, the pipe size should be designed with ample capacity which may be somewhat less than would be indicated by Table 6. The most common practice is to construct a main ditch system reaching the high points on each farm field then using the portable low pressure metal pipe as a moveable lateral system. These pipes usually have small gates in them, which are opened to serve the individual furrows. When this combination system is used, it is important to provide a trash screen at the inlet of the pipe to prevent clogging or the spreading of undesirable weed seeds.

High Pressure Pipe Lines.—High pressure farm irrigation systems are used to convey water for irrigation with sprinklers. Initial installation costs and annual costs are usually higher than for comparable open ditch or low pressure pipe line systems, but lands well adapted for surface methods of irrigation often can be successfully irrigated by sprinklers. The system may be either permanent buried pipe or portable metal pipe or a combination of the two. Since sprinkler systems are most efficient in use of water, with little seepage loss and little waste by deep percolation or field runoff, the recommended system capacity should be about one-half of that recommended for open ditches in Table 6.

Pressure systems are most commonly used in connection with pumping a water supply either from streams or wells, and in general the same pump will provide the pressure in the system as is used for diversion of the water supply. These systems usually operate under heads of not less than 20 psi and usually the head is about 40 psi. In some cases, water is supplied to farm fields in an open ditch system and by use of a portable pump and portable pipe sprinkler system the water is distributed over the field.

CONCLUSIONS

A complete plan for irrigating a farm should be prepared before installing a system. The farm should, as nearly as possible, be divided into permanent fields based on soils and topography, and a method selected for irrigating each field. This will provide the basis for designing the water supply and distribution systems. It will also help determine those fields which may require some modification to the topography by land grading. Table 8 is provided as a simplified aid in selecting the method or irrigation for various fields.

The final selection of the water supply and distribution system, methods of irrigating farm fields, and the types of crops to be grown will be dependent not only on the initial cost of development but also on the annual cost in materials and labor. Under present day conditions, the annual labor cost is of major importance.

Journal of the
IRRIGATION AND DRAINAGE DIVISION
Proceedings of the American Society of Civil Engineers

COMPUTER APPLICATIONS IN GROUNDWATER HYDROLOGY

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SYNOPSIS

The Theis equation is adapted for computer solution of four types of problems inherent in many industrial well-water developments. These types are (1) drawdown computation, (2) aquifer constants "T" and "S," (3) well spacing, and (4) capacity of a well system. Objectives, equations, computation sequence, print-out of results and computer time are outlined for each problem.

INTRODUCTION

Computer programs have been developed for the solution of four general types of hydrological problems. The objective in preparing these programs is to give the groundwater hydrologist a rapid and accurate means of solving these types of problems for any conditions specified or for any alternate value of a variable or variables. An alternate objective is to provide prepared mathematical solutions which engineers, who may have only a limited knowledge of the details of solving these types of problems, may use with confidence.

Whereas all of the variables involved in ground water hydrology may finally enter into the overall problem, those of main interest to the groundwater hydrologist are the two that define the characteristics of the aquifer; namely, the coefficient of storage, S and coefficient of transmissibility, T. In determining these, the usual procedure is to conduct an aquifer test, making observations of all the measurable variables. These include pumping rate, Q in gallons per minute, total drawdown, s, time, t, and the distance r to each observation well. Once this has been done, the aquifer characteristics can be

Note.—Discussion open until February 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 3, September, 1960.

[1] Cons., Engrg. Service Div., E. I. du Pont de Nemours and Co., Wilmington 98, Del.

determined by either (1) graphical solution using the "Type Curve" devised by Theis,[2] or (2) graphical solution devised by C. E. Jacob[3] on the basis of a modification of the non-equilibrium equation originated by Theis.

Generally, these two methods have been the most widely used in groundwater hydrology. Each involves the collection of numerous observations at frequent and brief intervals of time during a pumping test at essentially constant rate. In either case, it is necessary to pump a considerable length of time to get a large number of observations for plotting on appropriate graph paper. Data obtained from these plottings are then used in modified mathematical equations to compute the necessary aquifer constants. Once these have been determined, additional computation can be made to determine other items of importance with respect to the groundwater hydrology and the well water development. Supplementary plottings and computation are usually made for the study of such variables as long-term drawdown, increased pumping rates, variation of distances between permanent wells, the effect on well yield of interferences between wells, and the total number of wells required in the final installation to develop the full amount of well water desired. This work requires much valuable time which can be significantly reduced by utilization of a computer.

DRAWDOWN COMPUTATIONS

Program.—Drawdown computations involves drawdown in an observation well, at any time, by the non-equilibrium formula with known or assumed values of aquifer constants and pumping rate. This computer program solves for the drawdown "s" in an observation well by the Theis non-equilibrium equation.

$$s = \frac{114.6\ Q}{T}\left[-0.577216 - \ln u + \left(u - \frac{u^2}{2 \cdot 2!}\ \frac{u^3}{3 \cdot 3!} \cdots\right)\right] \quad .\ .\ (1)$$

in which $u = \dfrac{1.87\ r^2\ S}{T\ t}$ and $\ln = \log_e$

The computation is based on the fact that all factors in the equation have assigned constant values except s and t. In the solution of the problem, values of t are selected for which values of the drawdown s are to be computed. The objective of preparing a program for this type of solution is to provide a rapid and accurate method for computing drawdowns for a variety of conditions. It eliminates the necessity of resorting to graphs, tables or formulas.

The practical uses for this program might include the following:

1. Forecasting performance of a number of observation wells during an intended pumping test based upon assumed values of T and S.
2. Readjusting the spacing of observation wells to insure significant drawdown observations within the scope of an intended pumping test.

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2 "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground Water Storage," by C. V. Theis, Transactions, Am. Geophysical Union, pt. 2, 1935, pp. 519-524.

3 "Drawdown Test to Determine Effective Radius of Artesian Well," by C. E. Jacob, Proceedings, ASCE, May, 1946, pp. 629-646.

3. Determining the limit of time for test pumping, beyond which the rate of drawdown per day in any observation well may be insignificant with respect to other factors affecting water level.

4. Conducting a rapid check on the accuracy of computed values of T and S by computing drawdowns for comparison with test observations.

In the solution, values are assigned to S and T. Actual values for the type of formation may be available from other tests. The values may also be estimated based upon known geology, possibly from geological test holes drilled at the site to determine the depth, thickness and extent of water-bearing formations. Normally, the value of r is known for each observation well as is Q, the intended pumping rate. The only unknowns than are s and t. Therefore, s may be solved for any specified value or series of values of t.

Computation Sequence.—Generally, the computer procedure involves the operations of computation, control tests on magnitude of values, placing values in working storage, print-out of desired values and recomputation for successive values of t. The sequence that follows illustrates the computer procedure devised by J. L. Hertig.

Compute "u" - Test
Compute Series Term - Test
Add Series Terms
Subtr Ln "u"
Subtr 0.577216
Compute "s"
Compute Δs
Print Out
Test "t" - Test Δs - Test Counter - Stop Comp.
Recompute for next
value of "t"

Control Tests.—The program contains the following control tests of particular significance with relation to limiting the computations to the proper hydrologic scope.

For series term error.—As long as the value of u exceeds the factorial number in the denominator, the value of the series term is increasing. After this the value decreases and reaches a value beyond which it has no significant effect upon the computations. An error factor has been specified such that the computer will stop computing series terms when the value of a series term becomes less than the error factor. This factor is an item of input data and can be changed if desired.

For rate of drawdown.—The main portion of computation in the computer program involves computing the drawdown for each successive day of pumping. A control figure has been included as a part of input data which will stop this portion of the computations when the increment of drawdown from one day to the next is less than the specified control figure. This control figure may be assigned any value desired.

Data Print-Out.—Fig. 1 is a sample of the print-out obtained as computations are completed. Note that it first prints the assigned input data values of T, S, r and Q. This is then followed by a tabulation listing first the values of t as specified, then the corresponding computed values of the drawdown s. This is the actual print-out as made by the computer. It is referred to as floating

decimal form. In the floating decimal form, the decimal is always printed in the same place as shown. The two digit number immediately to the right of the seven digit number indicates correct location for the decimal point with reference to the printed location. The two digit number specifies the number of places which the decimal is to be moved. This movement is to the left if followed by a minus sign, otherwise to the right. Fig. 2 is the same data edited in fixed decimal form and is shown as a matter of information.

Note that the computer always prints out a seven-digit number as in Fig. 1 irrespective of the number of significant figures usable as shown in Fig. 2. Also, computers such as the LGP-30 (that used by the author), which must convert a decimal number to a binary floating point for internal processing, are subject to a tiny error in conversion called truncation error. For example, the first value of t = 0.354 is printed by the computer in Fig. 1 as 0.3539999.

During the process of computation, numerous values computed are placed in working storage in the computer. For any given value of "t," the values placed

GROUND WATER CALCS.

T		.1890000	05
S		.3849999	03-
r		.2030000	04
Q		.8250000	03
t		s	
.3539999	00	.3177059	01
.5000000	00	.4363727	01
.7079999	00	.5695532	01
.1000000	01	.7129710	01
.2000000	01	.1022758	02
.3000000	01	.1213270	02
.4000000	01	.1350636	02
.1000000	02	.1797221	02
.1000000	03	.2941994	02
.1000000	04	.4093049	02

FIG. 1.—COMPUTER PRINT-OUT (FLOATING DECIMAL FORM)

GROUND WATER CALCS.

T	=	18,900
S	=	.000385
r	=	2030
Q	=	825
t		s
	0.354	3.18
	0.500	4.36
	0.708	5.70
	1.00	7.13
	2.0	10.23
	3.0	12.13
	4.0	13.51
	10	17.97
	100	29.42
	1000	40.93

FIG. 2.—EDITED PRINT-OUT (FIXED DECIMAL FORM)

in working storage may be retrieved and printed if desired. For example, Fig. 3 is an alternate print-out of data from the same problem as Fig. 1. The headings of the various columns will be recognized as factors which are of specific interest in most groundwater computations. The computation and print-out of each line of data shown in these figures requires only about 30 sec.

Scope of Problem.—In this program, the scope of the computations is limited only by the number of values of t for which the hydrologist desires values of drawdown. For purposes of computation, these values of t are divided into three classifications.

1. Values of t less than one day: Any number of values of t up to eighteen can be specified. These individual specific values of t are entered as input data in order of increasing magnitude. The computer will take them in this order and compute the value of s corresponding to each.

2. Values of t for whole days: After completing the computations for all values of t less than one, the computer will begin calculating drawdowns for

successive days until the rate of drawdown from one day to the next becomes less than the control figure as explained previously. No input data are required for this step in the program.

3. Long term values of t: When the computer has completed the computations in step 2, it then goes to the computation of drawdowns for specific long-term values of t. Provision has been made in the program to include as many as nine specific long-term values for t. When the computer has completed computations of the specified long-term values of t, it will automatically stop and reset itself to receive alterations to the input data.

Time.—An estimate of the total amount of time involved in completely handling a problem containing ten values of t would show the preparation for the initial run to involve 15 min for input data sheets, 5 min for checking computer sub-routines, 1 min for loading program tape, 3 min for loading input data,

GROUND WATER CALCS.

T	.1890000	05
S	.3849999	03-
r	.2030000	04
Q	.8250000	03

t		u		W(u)		s		Δs		R	
.3539999	00	.4434343	00	.6351095	00	.3177059	01	.3177059	01	.2283298	04
.5000000	00	.3139514	00	.8723302	00	.4363727	01	.1186668	01	.2713602	04
.7079999	00	.2217171	00	.1138564	01	.5695532	01	.1331804	01	.3229072	04
.1000000	01	.1569757	00	.1425263	01	.7129710	01	.1434179	01	.3837612	04
.2000000	01	.7848786	01-	.2044543	01	.1022758	02	.3097873	01	.5427203	04
.3000000	01	.5232524	01-	.2425385	01	.1213270	02	.1905119	01	.6646939	04
.4000000	01	.3924393	01-	.2699986	01	.1350636	02	.1373657	01	.7675225	04
.1000000	02	.1569757	01-	.3592731	01	.1797221	02	.4465850	01	.1213559	05
.1000000	03	.1569757	02-	.5881188	01	.2941994	02	.1144773	02	.3837612	05
.1000000	04	.1569757	03-	.8182203	01	.4093049	02	.1151056	02	.1213560	06

FIG. 3.—DRAWDOWN COMPUTATIONS ALTERNATE PRINT-OUT

and 4 min for the computer accuracy check. The operation (involving computation and print-out) takes 5 min making a total time of initial run of 33 min. The supplementary runs involve 2 min to prepare and alter data, and 5 min for operation - computation and print-out producing a total time of 7 min.

AQUIFER CONSTANTS FROM TEST DATA

Program.—Aquifer constants from test data involved solution for coefficients of transmissibility and storage using data obtained during an aquifer pumping test. This computer program has been designed to take successive observations of drawdown and time and compute values of S and T that fit the Theis equation.

With an electronic computer a mathematical solution of the Theis equation can be obtained in a relatively short time with a minimum of two observations of drawdown and time. A series of values of S and T can also be obtained, each related to specific observations.

Unlike the graphical methods, numerous observations immediately after pumping starts are not necessary. Relatively few observations, several hours after pumping starts probably will constitute the most useful computer data, in the majority of cases. If a pumping test runs longer than one day, a few observations each day may be adequate for computer purposes.

Major advantages of the computer solution are as follows:

1. Elimination of the hectic pace at the beginning of a pumping test to obtain numerous drawdown and time observations.
2. Reduction in the quantity of data, the number of recorders and the personnel required to obtain observations.
3. Elimination of the need for plotting, together with the need for estimating match points and/or slopes.
4. Replacement of the single average S and T obtained graphically with a series of specific S and T values.
5. Attainment of valid values of S and T regardless of the rates of change of drawdown with time.
6. Reduction of time required to process data from numerous observation wells.
7. Utilization of fragmentary data from interrupted well tests to obtain usable results.

This particular program has been prepared to be run in two steps. Step 1 is identified as the short computation. It is a direct rapid solution that will give approximate values of T and S for use as trial values in the next step. Step 2 is identified as the long computation. It is a trial and error solution for T and S in the Theis equation.

In Step 1 a modified equation (normally used for large values of t only) is used. Values of drawdown and time in days after start of pumping are entered in sequence as data. The computer uses the values of s and t in sequence and in a pre-selected system of "pairs." It computes values of "T" from the equation

$$s_2 - s_1 = \frac{114.6\ Q}{T} \ln \frac{t_2}{t_1} \qquad (2)$$

It also computes "t_o" and then computes values of S from the equation

$$S = \frac{0.3\ T\ t_o}{r^2} \qquad (3)$$

Since these are straightforward computations, they can be done very fast. From the results obtained, selected answers are used as initial trial values in the next step.

In Step 2, the procedure used for computer solution was devised by J. W. Blakemore and R. C. Haines. It was applied to the general purpose computer by the writer. These procedures involve initial substitution of approximate values for S and T, computation of the resulting error in the computer drawdown s, and finally convergence to the actual "S" and "T" by a modified Newton-Raphson technique.[4]

Computation Sequence.—In the solution, the computation of s is by the method previously described. Generally, the same limitations and controls apply. As previously explained, the solution is fundamentally a trial and error method.

[4] "Introduction to Numerical Analysis," by F. B. Hildebrand, McGraw-Hill Book Co., Inc., New York, 1956, p. 447.

A direct mathematical solution is impossible. A trial and error solution of this magnitude is practical only because of the speed with which a computer can operate. An outline of the computation sequence in Step 2 is as follows.

Initial observations "s_1" and "t_1"

Trial values S_o and T_o

Calc "s"

Calc error in "s"

Trial values S_1 and T_o

Calc "s"

Calc error in "s"

Calc % error in "s" - Test

Calc new "S" by Newton-Raphson

Trial values S_{calc} and T_o

Re-calc "s" and % error - Test

Observations "s_2" and "t_2"

Values S_{calc} and T_o

Calc "s"

Calc error in "s"

Values S_{calc} and T_1

Calc "s"

Calc error in "s"

Calc % error in "s" - Test

Calc new T by Newton-Raphson

Re-calc "s" and % error - Test

First Run

Values S_o and T_{calc}

Compute diff. of T_o-T_{calc}

Start re-computation at the beginning

Compute diff. of $T_1 - T_{calc}$ ← Second Run

Calc % diff. - Test

Calc new T by Newton-Raphson

Start re-computation at the beginning

Print-Out

Bring "s_3" and "t_3"

Start next calc

Print-Out.—Fig. 4 is a sample print-out of computer results. The actual test flow rate Q in gallons per minute, and the distance to the observation well

```
AQUIFER CONSTANTS
SHORT COMP

Q               .8250000   03
r               .2030000   04

s               t                   S                 T
.3060000   01   .3559999   00
.9189999   01   .1750000   01   .2874686   03-   .2456073   05
.1023000   02   .2000000   01   .3072679   03-   .2141621   05
.1213000   02   .3000000   01   .3352084   03-   .2001697   05
.1261000   02   .3540000   01   .3065296   03-   .2180964   05
.1351000   02   .4000000   01   .3971055   03-   .1809220   05

LONG COMP

AQUIFER CONSTANTS

Q               .8250000   03
r               .2030000   04

s               t                   S                 T
.3060000   01   .3559999   00
.9189999   01   .1750000   01   .4020069   03-   .1979900   05
.1023000   02   .2000000   01   .4162171   03-   .1763371   05
.1213000   02   .3000000   01   .4272539   03-   .1764134   05
.1261000   02   .3540000   01   .3815286   03-   .1973939   05
.1351000   02   .4000000   01   .4313536   03-   .1769618   05
```

FIG. 4.—AQUIFER CONSTANTS FROM TEST DATA

r are printed first followed by a tabulation of the observed values of drawdown, s, and time, t, in proper order together with computed corresponding-values of S and T. Results for Step 1 are shown under Short Computation in Fig. 4. Those for Step 2 are shown under Long Computation of Fig. 4 and are the final computed results.

Time.—The total amount of time required to compute values of S and T in Fig. 4 are shown in Table 1.

These time requirements are reasonable when processing the data from a single observation well, or when using Step 1 only for a number of observation wells for which provision has been made in the program. On the other hand,

TABLE 1

Initial Run:	Time, in minutes	
	Step 1 Only	Steps 1 & 2 Combined
Preparation;		
Input data sheets and tapes	15	15
Check computer sub routines	5	5
Load program tape	3	3
Load input data	2	2
Computer accuracy check	1	17
Operation - Computation and print	5	30
Total time - Initial run	31	72
Supplementary Runs:		
Preparation; Data Sheets & Tapes	5	5
Load Data	2	2
Operation - Computation and Print	5	30
Total time	12	37

when data from numerous observation wells are to be run by the long computation, too much time is involved on the computer used. Other computers, that are faster at this operation shall be used in the future.

WELL SPACING

Program.—Well spacing involves the most economical spacing for a series of pumping wells based on consideration of the factors effecting both hydrology and cost. Recognizing that spacing a series of wells is a compromise between hydrology and total annual cost, this computer program was prepared for the combined solution of the nonequilibrium formula and the cost of a well system. The cost includes the complete cost of well, pump, motor, starter, pipeline between wells, power line and power. The hydrologic factors required are Q, specific capacity, S, T, maximum allowable drawdown s, and a value of t beyond which change in drawdown is relatively insignificant.

This program uses the Theis nonequilibrium equation to compute interferences and then develops the most economical number, pumping rate, and uniform spacing for a line of wells. The program as now prepared will handle up to nine wells of equal capacity.

The program starts by computing the minimum number of wells required to pump the specified total quantity of water. It computes spacing for these wells to provide minimum interference and to allow maximum utilization of the total allowable drawdown for pumping based upon specific capacity. It also computes the size of pipeline required for total output of well field. It then computes the total annual cost for the well system. Next the number of wells is increased by one and computations are repeated. The computer will continue to compute and print-out successive combinations of wells, pumping rates, interferences, spacings and costs in order of increasing number of wells. As the number of wells is increased, the spacing is decreased significantly, resulting in a lower investment and total annual cost. This will continue until the cost of adding wells exceeds the saving of reduced spacing. At this point the decreasing cost is reversed and an increase in total annual cost is obtained. The computer then stops.

The total drawdown was defined as

$$s = \frac{Q}{\text{Sp. Cap.}} + \Sigma s_1 \quad \dots\dots\dots\dots\dots\dots \quad (4)$$

in which s_1 = the drawdown due to interference from any single well, is defined by

$$s_1 = \frac{114.6\ Q}{T} [\, 0.577216 - \text{Ln}\ u] \quad \dots\dots\dots\dots \quad (5a)$$

This applies if short term values of t are not used. In this problem we are only concerned with relatively long term values of t. This equation can be rewritten as

$$s_1 = \frac{114.6\ Q}{T} \left[\text{Ln}\ \frac{T\ t}{1.87\ S} - 0.577216 - \text{Ln}\ r^2\right] \quad \dots\dots \quad (5b)$$

Letting $A = \frac{114.6\ Q}{T}$, and $B = \text{Ln}\ \frac{Tt}{1.87\ S} - 0.577216$ then

$$s_1 = A \left[B - \text{Ln}\ r^2\right] \quad \dots\dots\dots\dots\dots\dots \quad (5c)$$

For a series of wells in a line, the distance from the central well to wells on each side is r, 2r, 3r, 4r, and so on, where r is the uniform spacing between all the wells. Let N equal the number of wells and Σ series the sum of Ln of the multipliers for r, then the final equation to be solved is

$$\text{Ln}\ r = \frac{B}{2} - \frac{\Sigma s_1 + A\ [\,\Sigma\ \text{series}]}{2\ (N-1)\ A} \quad \dots\dots\dots\dots \quad (6)$$

In developing this program, consideration was given to the fact that nearly all industrial well-water systems are expanded by installation of additional wells in the future. Allowance is made for both present and future conditions in these computations by using the central well or wells as the "control" in computing the total drawdown due to interference. This figure is applied equally to all wells, even though it is recognized that, initially, the end wells will have significantly less interference. In this way, a uniform spacing for all present and future equal-capacity wells is obtained.

A maximum of nine wells in line was selected because this was adequate for interference computations on the central well of the systems considered in the initial problems. The computer has adequate capacity to handle much larger systems if necessary. It is a relatively simple job to rewrite the program when a system must consist of more than nine equal-capacity wells. An alternate procedure would be to simply prorate that portion of the total quantity of water than can be produced from a system of nine wells or less and then compute the most economical individual well capacity and spacing. This same capacity and spacing may be sufficiently accurate to apply to all wells in the system.

Computation Sequence.- As explained previously, the first step in developing this program was to rearrange the Theis equation for solution of r for any known t and known values of Q, S, T, specific capacity and number of wells. Using the computed values of r, the investment and annual cost related to distance are computed and totaled. The outline of a sequence used in the computer solution of this problem is as follows.

Calc Min. No. Wells

Calc DD due to Sp. Cap.

Calc allowable Σs_1

Calc B/2

Calc A

Calc Σ Series

Calc Ln r and r

Calc Cost of Power

Calc Well Invest.

Calc Power Line Invest.

Calc Pipe Diam. & Invest.

Calc Annual Fixed Chgs.

Calc Power for Pumping

Calc Total Annual Cost

Print-Out

Test Annual Cost

Increase N by 1

Re-compute

Fig. 5 is a print-out of results of a sample problem. The first tabulation is a listing of pertinent input data required, including both the hydrologic data and the unit cost data. The next tabulation gives the computed results starting with the computed minimum number of wells and adding one well each time until the variable investment (TOT INV) and annual cost (C) start to increase. At this point computation automatically stops and the computer resets itself to receive new data.

Fig. 6 is a plotting of these results, showing that the minimum portion of the cost curve is quite flat. The results must, therefore, be examined to select

the most favorable spacing that truly represents a significant economic saving in relation to the next larger spacing. One refinement in this program would be to stop the computation when a significant reduction in spacing results in only a minor reduction in cost.

WELL SPACING

S	.3849999	03-
T	.1890000	05
t	.3650000	03
s	.1000000	03
Sp Cap	.7399999	01
GPM	.2000000	04
Well $ ea	.2000000	05
Pipe $/"/ft	.1000000	01
Cable $/f	.4000000	01
$/KWH	.5999999	02-

N		Q		d		Σsi		Tot Inv		r		C	
.3000000	01	.6666666	03	.1400000	02	.9909911	01	.1490590	07	.3973861	05	.1520110	06
.4000000	01	.5000000	03	.1400000	02	.3243243	02	.6085870	06	.9788649	04	.6380983	05
.5000000	01	.4000000	03	.1400000	02	.4594594	02	.4497922	06	.4858226	04	.4793058	05
.6000000	01	.3333333	03	.1400000	02	.5495495	02	.3848225	06	.2942472	04	.4143369	05
.7000000	01	.2857142	03	.1400000	02	.6138948	02	.3674939	06	.2106428	04	.3970139	05
.7999999	01	.2500000	03	.1400000	02	.6621622	02	.3606139	06	.1592174	04	.3901338	05
.8999999	01	.2222222	03	.1400000	02	.6996996	02	.3658629	06	.1290715	04	.3953829	05

FIG. 5.—WELL SPACING

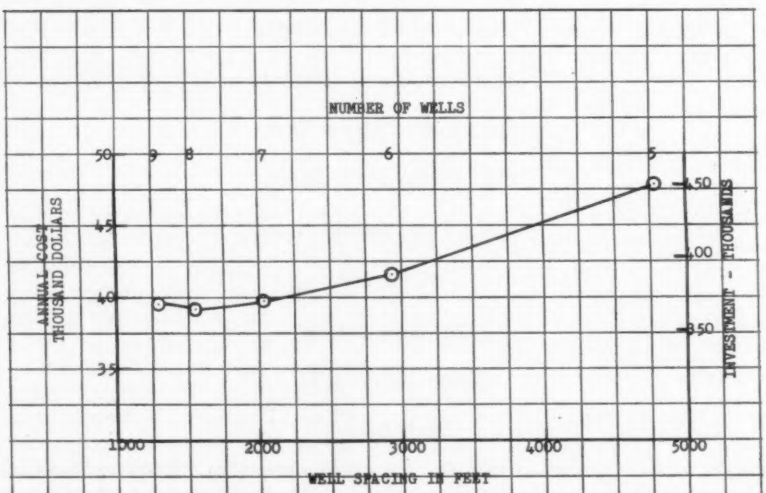

FIG. 6.—ECONOMIC SPACING OF WELLS

Time.—The approximate times required for a system of wells, within the scope of the program as prepared can be summarized. For the Initial run the Preparation involved 15 min for input data sheets, 5 min to check computer

sub routines, 3 min to load program tape, 3 min to load input data, and 4 min for the computer accuracy check. The operation, involving computing and print-out, took 6 min, causing a total time for the initial run of 36 min. The supplementary runs involved 2 min to prepare and load data, and 6 min for the operation (computing and print-out) producing a total time of 8 min.

CAPACITY OF A WELL SYSTEM

Program.—Capacity of a well system involves the capacity of a number of wells in any geometric configuration including existing pumping wells, standby well, future wells and recharge wells. The objective of this program is to provide the hydrologist with a rapid method for computing the collective capacity of a group of individual wells. This is a problem frequently encountered in both new and old well systems. Basically, a need for the use of this program would develop in the solution for one or more of the following situations affecting net well field capacity:

1. The interference of each pumping well upon every other well in a system.
2. The effect of starting and stopping selected wells.
3. The effect of drilling additional wells for expansion. Expected capacity of new wells and their effect on capacity of existing wells.
4. The potential capacity improvement with artificial recharge.
5. The overall effect of improving specific capacity by chemical cleaning.
6. The overall effect of significant changes in static water level.

As in previous problems, computations are based upon the Theis equation, however, in programming this type of problem it was recognized that all computations would involve relatively large values of t. Accordingly the following modified formula was used:

$$s = \frac{114.6\ Q}{T} \left[\ln \frac{T\ t}{1.87\ r^2\ S} - 0.577216 \right] \ldots\ldots\ldots \quad (7)$$

Since solution of this problem involves use of many different values of r as the interference effect of various wells is computed in sequence, the equation has been re-written in the form

$$s_1 = \frac{114.6\ Q}{T} \left[\mathrm{Ln}\ T + \mathrm{Ln} \frac{t}{1.87\ S} - 0.577216 \right] - \frac{114.6\ Q}{T} \mathrm{Ln}\ r^2 \ldots \quad (8a)$$

or

$$s_1 = A\,B - A\ \mathrm{Ln}\ r^2 \ldots\ldots\ldots\ldots\ldots\ldots \quad (8b)$$

the form of which is the adaptation used for the computer.

This program computes the amount of water than can be pumped from a system of irregularly spaced wells for any specified drawdown. It has a capacity for wells in any configuration of layout up to ten wells. Pumping wells, recharge wells, and standby wells can be included. It is very easy to vary the

number of wells for which computation is to be made, and to vary their pumping or recharge rates. The program will compute the time of pumping required to lower water levels to the specified allowable drawdown and will compute the radius of influence. If desired, a definite time can be specified for the computations.

The program begins by computing the interference that each well produces when pumped at a specified rate on every other well. When all interferences have been computed, the computer adds up the total interference for each well. This, together with the drawdown due to specific capacity, is then compared with the total allowable drawdown specified. A capacity pumping rate is then computed for each well by adjusting the total drawdown to the total allowable drawdown. This is the optimum pumping rate and the computer makes a new series of computations for each well using this optimum rate. Following this, the goal-capacity specified for the system is prorated to each well to take its optimum percentage of the goal capacity. The rate of flow and water level elevations are then computed for operation at this capacity.

The complete procedure as outlined is accomplished by essentially repeating the same cycle of computations three times. These computations cover performance at (1) precent capacity, (2) optimum capacity and (3) goal capacity. At the conclusion of each, a separate print-out is made. Between each series of computations a recomputation of Q is made and printed. At the end of the third series, the computer will automatically stop and reset itself to receive new data.

It will be recognized that each series of computations actually represents a problem condition with new data. Obviously some situations do not require answers to all three of these conditions. Provision has been made, therefore, to elect one, two or all three series of computations as desired.

Computation Sequence.—The following is a simplified sequence of procedure as set up for the computer:

Calc "t" and "R" (If not specified)

Calc A and B in equation for "s_1"

Calc values of "s_1" for each well at each "r"

Retain all values of "s_1" in working storage

Add values of s_1 to get Σs_1 for each well

Adjust each well rate to optimum

Compute total drawdown and elevation of water level

Print-Out

Modify: -

First Series - Replace "Q" with optimum - Repeat comp.

Second Series - Allocate goal "Q" to each well - Repeat comp.

Third Series - Stop computation

Print-Out.—Fig. 7 is a sample print-out obtained from this program for the series of computations only. As previously mentioned, three series of computations may be made. Each series will result in a print-out similar to the one shown. As before, the first tabulation is a print-out of pertinent input data. This is followed with a tabulation of the data for each well for which a computation has been made. This includes the well number, limiting s or total allowable drawdown, either the specified or computed rate of flow, the computed total interference indicated as Σsi, the total computed drawdown, and lastly the final computed elevation of the water level in each well.

In Fig. 7 the rate of flow for each well has been specified and the resulting water levels computed. In Fig. 8 the computer has altered the rate of flow of each well so that all wells are drawn-down approximately to the limiting s of 106 ft. The static level in the problem is at elevation -15 ft. Thus, the water level in each well is about at elevation -121. In Figs. 9 and 10 the same conditions as in Figs. 7 and 8 are computed, but with well No. 100 added as a recharge well at a fixed rate of 300 gpm. Note that this has a significant effect on water levels in the first series of computations (Fig. 9) and a significant effect on well capacity (gallons per minute) in the second series of computations (Fig. 10).

Time.—This program requires the following approximate times based upon a system of five wells for which all three series of computations are to be completed. The initial run involves preparation which requires 30 min for input data sheets, 5 min to check computer subroutines, 3 min to load program tape, 5 min to load input data, and 8 min for the computer accuracy check. The operation of computing and print-out involves 10 min for the first series, 10 min for the second series, and 10 min for the third series. Thus, the total time for the initial run is 81 min. Supplementary runs involve 3 min to prepare and load data, and 30 min for operation (10 min for each series,) for a total time of 33 min.

CONCLUSIONS

These accomplishments are but a small beginning in terms of the mathematical and technical potential for the application of computers in this field. With computers to handle the mathematical details, two significant results are probable. Specialists in ground water hydrology will be capable of more work of greater scope, including research in the application of mathematics. Others, specifically engineers with only a limited knowledge of ground water hydrology, will be able to utilize these prepared mathematical procedures as required to do better work faster.

A great deal of the cost involved in using computers is the cost of the technical time required for adapting the mathematics for use with a computer, planning the flow diagram, preparing the detailed program sheets, typing the program tape, and debugging the program to put it in perfect operating condi-

WELL CAPACITIES

T	.2000000	05
S	.2000000	03-
Tot GPM	.1200000	04
Lmtg "s"	.1060000	03
DAYS "t"	.1825000	04
CONE R	.2340000	06

WELL NO		Limtg"s"		GPM		Σsi		Tot DD		EL WL	
.7000000	01	.1060000	03	.3000000	03	.5482275	02	.7982275	02	.9482275-	02
.6000000	01	.1060000	03	.3000000	03	.5521810	02	.8021810	02	.9521811-	02
.4000000	01	.1060000	03	.3000000	03	.5642829	02	.8142829	02	.9642830-	02
.3000000	01	.1060000	03	.3000000	03	.5295722	02	.7795722	02	.9295722-	02

FIG. 7.—CAPACITY OF A WELL SYSTEM—FIRST SERIES OF COMPUTATIONS

WELL CAPACITIES

T	.2000000	05
S	.2000000	03-
Tot GPM	.1593245	04
Lmtg "s"	.1060000	03
DAYS "t"	.1825000	04
CONE R	.2340000	06

WELL NO		Limtg"s"		GPM		Σsi		Tot DD		EL WL	
.7000000	01	.1060000	03	.3983826	03	.7272193	02	.1059205	03	.1209205-	03
.6000000	01	.1060000	03	.3964192	03	.7337061	02	.1064055	03	.1214056-	03
.4000000	01	.1060000	03	.3905276	03	.7543666	02	.1079806	03	.1229806-	03
.3000000	01	.1060000	03	.4079160	03	.6970033	02	.1036933	03	.1186933-	03

FIG. 8.—CAPACITY OF A WELL SYSTEM—SECOND SERIES OF COMPUTATIONS

WELL CAPACITIES

T	.2000000	05
S	.2000000	03-
Tot GPM	.1200000	04
Lmtg "s"	.1060000	03
DAYS "t"	.1825000	04
CONE R	.2340000	06

WELL NO		Limtg"s"		GPM		Σsi		Tot DD		EL WL	
.7000000	01	.1271396	03	.3000000	03	.5482275	02	.7982275	02	.7368310-	02
.6000000	01	.1262909	03	.3000000	03	.5521810	02	.8021810	02	.7492717-	02
.4000000	01	.1261334	03	.3000000	03	.5642829	02	.8142829	02	.7629485-	02
.3000000	01	.1236743	03	.3000000	03	.5295722	02	.7795722	02	.7528293-	02
.1000000	03	.1000000-	03	.3000000-	03	.7923833	02	.5423832	02	.6923833-	02

FIG. 9.—CAPACITY OF A WELL SYSTEM—FIRST SERIES—WITH RECHARGE WELL

WELL CAPACITIES

T
S
Tot GPM
Lmtg "s"
DAYS "t"
CONE R

WELL NO		Limtg"s"		GPM		Σsi		Tot DD		EL WL	
.7000000	01	.1271396	03	.4778323	03	.8604946	02	.1258688	03	.1197292-	03
.6000000	01	.1262909	03	.4723034	03	.8703225	02	.1263909	03	.1210999-	03
.4000000	01	.1261334	03	.4647037	03	.8941100	02	.1281363	03	.1230029-	03
.3000000	01	.1236743	03	.4759313	03	.8318137	02	.1228423	03	.1201680-	03
.1000000	03	.1000000-	03	.3000000-	03	.1248418	03	.9984176	02	.1148418-	03

FIG. 10.—CAPACITY OF A WELL SYSTEM—SECOND SERIES—WITH RECHARGE WELL

tion. Once this has been completed, significant savings in time and cost begin to be realized as opportunities develop for reuse of the program on repeated problems.

SUMMARY

Four problems have been programmed for use on a general purpose computer. In addition, the problem of determining aquifer constants from test data has been programmed on the Univac. The economics of this type of work dictate the use of a computer only when the scope of the job is of such magnitude that considerable time and engineering cost can be saved over previously used testing, graphical, and manual computing methods.

In such cases, a decision is needed as to what type and size of computer is justified. It would appear that the first two types of problems are more adaptable to a digital computer, whereas the latter two are more suitable to an analog. While this may be technically correct, the most important consideration is to provide flexible programs for these hydrologic problems which can be repeatedly used on a single readily available computer with minimum effort and at minimum cost. A general purpose digital computer is a practical selection.

ACKNOWLEDGMENTS

The computer procedures described herein were devised at the Engineering Service Division of the E. I. DuPont de Nemours Co. of Wilmington, Delaware.

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Journal of the
IRRIGATION AND DRAINAGE DIVISION
Proceedings of the American Society of Civil Engineers

IRRIGATION IN LATIN AMERICA[a]

By Lyman A. Willardson,[1] A.M. ASCE

SYNOPSIS

Irrigation agriculture in three representative Latin American countries needs competent technological guidance to utilize the potential of unusual tropical conditions. Non-uniform annual distribution of rainfall combined with ideal soil and twelve-month growing season favor high agricultural development in these representative Latin American countries through supplemental irrigation, coupled with coexistent drainage of excess rainfall during wet seasons.

INTRODUCTION

Irrigation in the tropical regions of Latin America is increasing in importance. The need for more efficient agricultural production coupled with understanding of climatic factors has shown that production improvements can be accomplished by irrigation. Microclimates and dry seasons which limit productivity occur in many areas having tremendous production potential.

The irrigation developments in the tropics up to the present time have been largely a result of necessity, but their success indicates that irrigated agriculture is only beginning to develop there.

The three countries reported here might be considered as an introduction to irrigation agriculture in the tropics. The degree of development, the approach to development, and the interest in development of the irrigation poten-

Note.—Discussion open until February 1, 1961. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 3, September, 1960.

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tial in each of the countries is considerably different. This report is intended to describe the range of conditions that exist.

REPUBLIC OF HONDURAS

The Republic of Honduras is the second largest country in Central America. It is democratic and governed by an elected president. The people are Spanish and Indian, and Spanish is the national language. The climate is tropical and there are many heavy tropical jungles complete with all the typical jungle fauna. The lowlands are hot and humid, but the mountains have a somewhat cooler, more agreeable climate.

The land resources of the country have undergone only limited development because of problems which are at least partially connected to climate. Agriculture is practiced mostly by individuals on a small scale. Typical farming is done by burning and clearing a patch of land during the dry season for one or two seasons' planting during the rainy season. The country is still classified as 95 % forest, woodland, or wasteland. The remaining 5 % is divided between meadow and pastureland (1.4 %) and arable and orchard land (3.6%).

The single most important agricultural crop of Honduras and the most intensively cultivated one is bananas. They are grown on about 5.5 % of the cultivated land, but they account for 65 % of the total exports of the country. Nearly 12,000,000 stems of fruit are shipped annually and the value of the crop is about $35,000,000.

Government activity in the development of irrigation projects in Honduras has been quite limited. In 1950, the FAO reported 50,000 acres of irrigated land in the country and showed no irrigation projects under construction and none planned. These 50,000 acres were primarily planted to bananas. In 1956, a census report lists 56,000 acres of bananas and a production of 15,500 tons of rice. The rice grown in Honduras is mostly of the upland variety which does not require irrigation; therefore, the 56,000 acres listed for bananas is very nearly the irrigated acreage in that year.

Irrigation of bananas in the hot humid tropics sound like somewhat of an anomaly but there is little difference between irrigation there and irrigation in our own humid areas. Twenty-six years of records on the Buena Vista farm show a maximum annual rainfall of 60 in. Monthly rainfall varies from a minimum of zero in the dry season to a maximum of 22 in. in the wet season (Table 1). Sixty inches sounds like a lot of rain, but when the time distribution is examined and cognizance given to the fact of a 12-month growing season, the need for irrigation is immediately apparent, as indicated in Table 1. The wet season in the banana areas usually begins in June and lasts through December, but during these months irrigation is sometimes required. Irrigation is done on the basis of experience and judgment. Although some research has been done on consumptive use and controlled irrigation, the evapotranspiration needs of bananas is not precisely known. Bananas have an 11- to 12-month growth cycle and require adequate moisture and drainage during all of that period to produce good fruit continuously.

The pioneer in banana irrigation in the tropics has been the United Fruit Company of Boston. By irrigation and drainage they have effectively reclaimed many thousands of acres of jungle-covered wasteland for successful banana production. Without irrigation, it is doubtful if their operation would be a continuing success.

Most of their banana irrigation is by means of overhead sprinklers, but there is also some acreage irrigated by undertree sprinklers, borders, and wild flooding. The overhead sprinklers they use were developed by their own research department. The sprinkler heads operate on 95 psi pressure and are mounted on 4-in. riser pipes 25 ft high, spaced 400 ft apart in a triangular pattern. They each deliver 500 gpm and cover 3.34 acres. A small turbine and gear arrangement rotates the sprinkler.

The gross water application for various irrigation methods on United Fruit farms if 8.3 in. per week for wild flooding, 5.6 in. per week for basins, 2.0 in. per week for overhead sprinklers, and 1.5 in. per week for undertree sprinklers. This gives an interesting comparison between the efficiency of their various irrigation systems, since the consumptive use of the plants should be nearly the same regardless of the method of water application.

TABLE 1.—MONTHLY RAINFALL 1922-1948, BUENA VISTA FARM, REPUBLIC OF HONDURAS

Month	Rainfall, in inches			
	Mean	Median[a]	Minimum	Maximum
(1)	(2)	(3)	(4)	(5)
January	4.26	3.82	0.57	13.11
February	2.44	2.07	0.00	10.98
March	1.84	1.00	0.04	7.35
April	1.40	0.77	0.00	7.05
May	3.11	2.96	0.10	8.70
June	5.67	5.35	0.00	12.69
July	6.56	6.28	2.44	13.38
August	5.79	5.31	2.60	12.91
September	6.92	7.93	1.31	14.36
October	7.02	6.15	1.90	14.27
November	10.11	8.50	2.98	22.14
December	5.59	5.67	1.78	13.00
Annual	60.71			

[a] Half the years of record show greater or less rainfall.

In the tropics, as elsewhere, irrigation and drainage must be coexistent. Experience has shown that drains 5.5 ft to 6.5 ft deep with a 2-ft bottom and 1 to 1 side slopes on 250-ft centers are necessary for sustained banana production. These are designed with a 2.4-in. runoff modulus for quick water removal in the wet season and undoubtedly provide important subsoil drainage during the irrigation season.

Irrigation agriculture in the tropics is just beginning. Until very recently the technology to control the unusual tropical conditions has not been available. New developments including heavy equipment for land clearing and rapid land preparation and new herbicides, insecticides, and fungicides should open a new era of food production in tropical countries. Engineers are generally aware

that present world food surpluses are temporary and localized and that new land development will be needed. Irrigation of tropical lands is a new frontier which needs increased attention.

DOMINICAN REPUBLIC

The Dominican Republic is an important Carribean country located in the greater Antilles Islands. Its heritage and the language spoken is Spanish. It has an interesting history and many tangible reminders of the past including the remains of Columbus, the oldest cathedral in the western hemisphere (completed in 1540), and the restored castle of Don Diego, son of Columbus.

The first settler arrived in 1496 and development of the island's resources has been continuous ever since. Progress in irrigation development is perhaps the most spectacular of any of the Latin American countries and has mainly taken place in recent years. The island is very mountainous, approximately 49 % of the land area being classified as forest, woodland, or wasteland. Fifteen % is arable and orchard land and 26 % is meadow or pasture land.

Sugar, coffee, cocoa, tobacco, and bananas are the principal export crops grown in the Dominican Republic. Rice is important domestically and most of the irrigation projects have been developed for rice growing. Bananas are irrigated on the north coast and there is some irrigation of sugarcane plantations.

The island has a wide variety of climatic conditions. These are due to topography which affects temperatures, wind, and rainfall. More than 30 % of the country is classified as arid, which may account for the extensive irrigation developments. Annual rainfall varies from 20 in. in the south to 100 in. in the central mountains. The month of minimum rainfall (March) delivers about 1 in. to most of the island. The wettest month (May) leaves 6 in. to 10 in. The average annual temperature in the coastal regions is about 77° F with only plus or minus 10° extreme variation during the year. The year long uniformity of day length characteristic of this latitude, plus a favorable growing temperature 12 months of the year and the accompanying long /eriods of low rainfall, make irrigation essential for full production of many crops. Fig. 1 shows lines of equal annual precipitation in millimeters.

Modern history in the Dominican Republic is dated from 1930 when Generalissimo Rafael Leonidas Trujillo Molina came to power. The government since then has been actively engaged in irrigation development. Agriculture is the principal resource of the Dominican Republic and exploitation of that resource requires irrigation. The present government has apparently recognized this fact.

In 1930 there were only 7,500 acres of land irrigated under government projects. By 1942 the total had grown to 37,500 acres and an additional 32,000 acres were being irrigated by private canals. At the end of 1944, the total area for canals completed was 85,000 acres. The data available at the end of 1945 for canals completed, those under construction, planned enlargements, and new areas under study, totaled 221,000 acres. The area under government irrigation projects in 1959 has reached 380,000 acres. The rapid growth of irrigation project development which began during World War II has continued to the present time.

The acreages reported are those given in the project designs. The actual irrigated area is normally somewhat less. In 1944, for example, 51 % of the total area in the projects was irrigated, although one canal reported irrigating

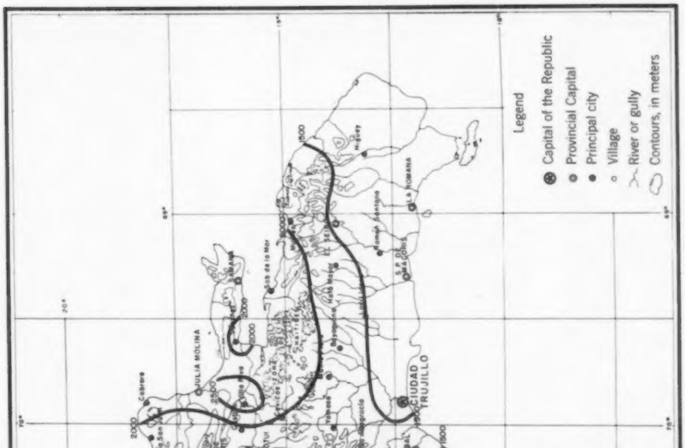

FIG. 1.—LINES OF EQUAL ANNUAL PRECIPITATION

107 % of its design area. No data are available on actual irrigated acreage in 1959.

The Dominican Government is interested in new irrigation projects. It has effected the past development with its own resources and have built some unusual and economical projects. Most of the canals are unlined and divert water directly from the rivers. Their capacities vary from 6 cfs to 425 cfs, with an average of 70 cfs.

The control structures are made of concrete and are conventional with a few exceptions. The stepped drop of 46 ft in the Nizao lateral of the Marcos A. Cabral Canal and the flume of the Presidente Trujillo Canal are examples of unusual structures. Most of the flumes, dividers, spillways, and gates are of rather simple design. On some of the flumes, leather was used to cover the open expansion joints left between the cast sections. Fig. 2 shows the stepped drop of the Marcos A. Cabral canal, and Fig. 3 shows the flume of the Presidente Trujillo Canal.

By taking advantage of favorable natural conditions, the Dominican Government, according to data provided by the Secretary of State of Agriculture, has been able to develop 380,000 acres of irrigation projects at an average cost of only $72.00 per acre. When the 12-month growing season is considered, this cost per acre is very low. Future developments will probably be more expensive, requiring dams, reservoirs, desilting works, and other requirements. In addition, at the present time, there is some interference and competition for water on streams which have developed diversions exceeding their minimum flows.

The present status of plans by the Dominican Government for multi-purpose project development is unknown. It does, however, have some potential for hydroelectric installations which would take advantage of energy now being wasted.

There is also room for improvement in the efficient use of irrigation water, as there is in all countries. Analysis of canal capacities and actual irrigated areas indicates a variation of from 4.4 acres to 70 acres irrigated for each cfs of canal capacity. Better management of water could bring these projects up to their full design acreages. The extent of drainage problems associated with the reported irrigation projects is also unknown and this may have a bearing on the reduced project acreages below those designed.

Full development of the irrigated agriculture potential in the Dominican Republic will depend on the interest of the government and on the education of the people to take full advantage of modern agricultural advances.

PUERTO RICO

Puerto Rico, an island located in the West Indies, is part of the United States having commonwealth status. It is about 110 miles long and averages about 40 miles in width. The total area is 3,435 sq miles. The center of the island is very mountainous with the highest peak rising to nearly 4,400 ft. The coastline consists principally of a narrow fertile plain which slopes upward toward the mountains. The climate ranges from tropical to subtropical and the rainfall varies from 30 in. to 200 ins. annually depending on location, with these extremes being only 70 miles apart. Within this small area, there are 115 soil series with 325 types and phases.

FIG. 2.—STEPPED DROP OF THE MARCOS A. CABRAL CANAL

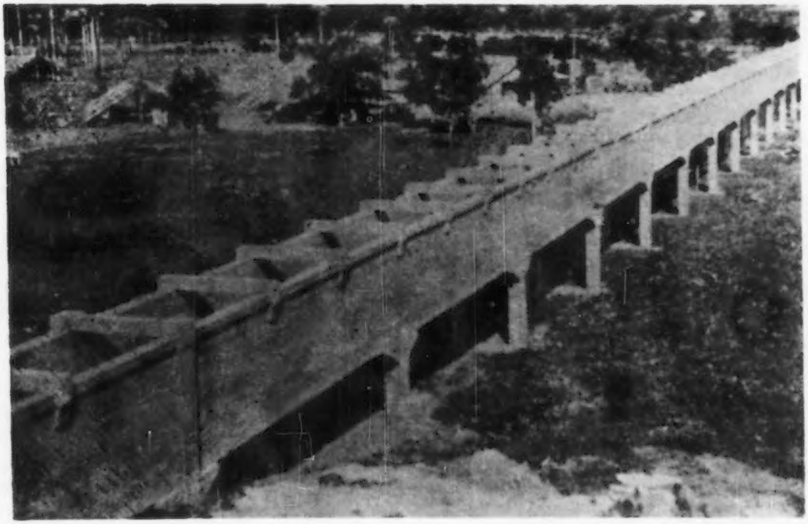

FIG. 3.—FLUME OF THE PRESIDENTE TRUJILLO CANAL

The majority of Puerto Ricans are of Spanish descent with 20 % or more being Negro and mixed bloods. Spanish is the language spoken commonly, but many of the people speak English. Puerto Ricans have full United States citizenship rights and migrate freely to and from the United States.

The economy of Puerto Rico is based on agriculture because of lack of other natural resources, but recently there has been an industrialization program ("Operation Bootstrap") encouraged by tax exemption incentives which has helped to improve employment conditions. Sugar cane is the principal crop and is the crop grown on most of the irrigated acreage.

In spite of a mountainous interior, only 28 % of the island is classified as forest, woodland, and wasteland. Forty-five % is arable and orchard land, and 27 % is permanent meadow and pasture. Some of the land cultivated is on very steep slopes which are unfavorable to irrigation development.

The first irrigation in Puerto Rico was developed on the dry south coast while the island was still under Spanish domination. Here the quantity and distribution of rainfall are insufficient for sugar cane production on the otherwise excellent soils. By the middle of the 1800's, the Spanish Crown had granted water rights for irrigation to some of the landholders. The present government has recognized these rights, and irrigation under them has been practiced continuously.

The development of irrigation projects by the Insular Government began in 1909 and has continued to the present time. This development closely parallels the reclamation of land by irrigation in western United States which began in 1902. At present, there are about 65,000 acres of land under irrigation on the south and northwest coasts. With approximately 770,000 acres total cropland on the island it means that less than 10 % of the agricultural cropland is irrigated.

IRRIGATION PROJECTS

The three principal irrigation projects on the island which have been sponsored by the Puerto Rican Government are:

1. The South Coast Irrigation District
2. The Isabela Irrigation Service
3. The Southwestern Puerto Rico Project

The latter project is still under development.

The South Coast Irrigation District was the first and largest of the three government projects. An area of 33,000 acres is irrigated by gravity flow from storage reservoirs and an additional 18,000 acres is irrigated by pumps and wells.

The water allotment is fixed by the Public Irrigation Law at 4 acre ft per acre per yr, delivered continuously and uniformly. This quantity of water has proved adequate to supplement rainfall on most farms. Where exceptionally permeable soils are found, farmers have drilled wells to increase their supply. The farms in the district pay a rate of about $15.00 per acre per yr for water or slightly less than $4.00 per acre ft. Irrigation in this area has been responsible for an increase of 400 % in sugar production since the project was completed in 1914.

The Isabela Irrigation Service on the northwest corner of the island was the second irrigation development sponsored by the government. It was origin-

ally designed to irrigate 18,000 acres, But porous canal beds and sinkholes have reduced the size of the project to only 8,300 acres actually under irrigation. In contrast to the south coast project which delivers water to large farms, more than 600 of the 780 farms served by the Isabela canal are 10 acres or less in size. About 80 % of the acreage irrigated is in sugar cane with the remainder in cotton, corn, tobacco and vegetables.

Water charges in this area are $0.70 per acre ft for farms of 10 acres or less and ρ2.30 per acre ft for farms of 100 acres, the charge depending on farm size. Additional water above the 1.5 acre ft per acre allotment is available at $2.00 per acre ft. In spite of the low water charges there is not much interest by local farmers in using the irrigation water available.

Reducing the irrigated area from 18,000 to 8,000 acres imposed such a heavy financial burden on the irrigation phase of the project that additional power facilities had to be developed to meet the repayment schedule.

The Southwestern Puerto Rico Project is presently under development. It is a multi-purpose reclamation type undertaking which has all the usual facets, including diversion of water from one watershed to another. Although small by some standards (26,000 irrigated acres) it will, when completed, increase the irrigated area of Puerto Rico by 35%. The Lajas Valley, in which the project is located, is on the southwest corner of the island which receives an average of about 40 in. of rainfall. The minimum recorded rainfall is 10 in. and there are a number of years with less than 20 in. Fig 4 shows a map of the Lajas Valley project. The valley is from 1 to 3 miles wide with hydrologic conditions such that cactus and mesquite grow on one side while sugar cane grows without irrigation on the other side.

The water storage and hydroelectric phases of the project are almost complete and considerable drainage work has been done. The valley has some serious drainage problems which include saline and alkaline soils of low permeability over an artesian aquifer. More than 30 % of the canals and distribution laterals have been constructed. These are designed to carry 5 acre ft per acre per yr to each farm at a continuous and uniform flow rate.

Although only three years have passed since the first water was delivered in the project, and in spite of the fact that less than 25 % of the area is receiving water, the agricultural income in the valley has increased from $2,000,000 to $4,000,000 per yr.

So far the principal crop planted on project lands has been sugar cane, but this valley offers almost unlimited possibilities for diversification. Specialty crops for United States markets during the winter months are attractive possibilities. Cantaloupes grown there on an experimental basis retailed for $1.25 each on the New York market in December.

NEW AREA POSSIBILITIES

In addition to the water supply for the 85,000 acres now developed in irrigation projects, there is sufficient unregulated minimum flow in rivers running into the sea to irrigate an additional 36,000 acres. Storage and multipurpose projects might expand this still further. Undeveloped hydroelectric power from these same rivers amounts to more than a billion kilowatt hours annually. The Puerto Rico Water Resources Authority, an agency similar to the United States Bureau of Reclamation, is presently studying some of these possibilities.

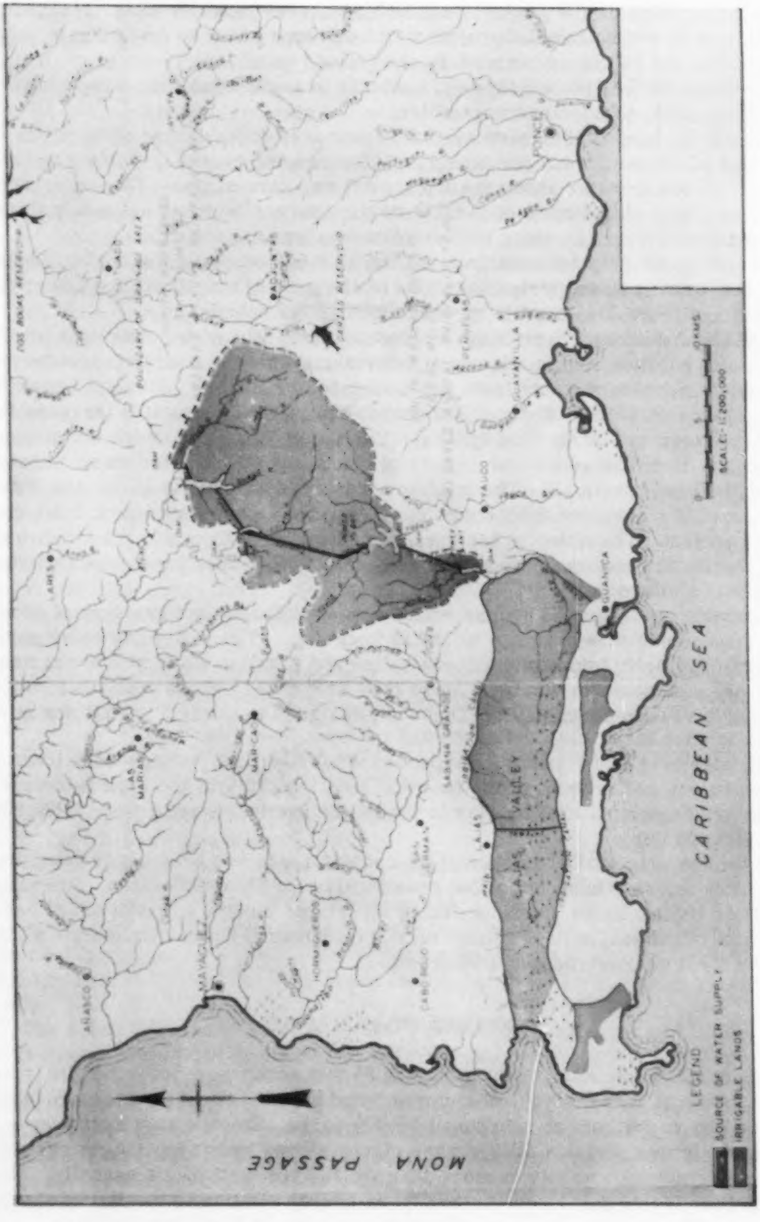

FIG. 4.–MAP OF THE LAJAS VALLEY PROJECT

In the next few years there will likely be an upsurge of interest in irrigation in the higher rainfall areas of the island. High annual rainfall does not eliminate dry seasons and dry spells during which irrigation can show tremendous returns. Sprinkler irrigation on pastures and specialized crops has already begun to a limited extent.

GENERAL AGRICULTURAL PROBLEMS

An important deterrent to the development of irrigation on a general scale in Puerto Rico is the lack of individual farmer interest in diversification of agriculture. Sugar is dominant, and continues to grow and produce during dry periods when more intensive crops require irrigation and considerable other attention. Sugar cane can be left alone for 8 to 10 months of the year in most areas with no labor or cultivation being required. Diversification of agriculture might require radical changes in the whole social structure of a society which has developed in a sugar cane economy.

The Soil Conservation Service has the whole island organized into districts and is providing excellent assistance to the farmers. The University of Puerto Rico has a fully organized Extension Service and an excellent Agricultural Experiment Station system which is providing information and education for agricultural improvement. These agencies are performing a very important function on the island.

EMBASSADORIAL ROLE OF PUERTO RICO

Puerto Rico enjoys a unique position in United States-Latin American relations. It is one of the most advanced Latin American countries and operates as a showcase of American ways where Latins can come and learn about America in their own language, shown to them by people like themselves, with the same cultural background. A visitor from South America to the United States who has stopped first in Puerto Rico is more able to appreciate what he sees here. American agricultural technology has developed under our particular conditions and is not always directly applicable in other countries. Adaptations and modifications of this technology in Puerto Rico may assist in its quick acceptance in other tropical countries.

CONCLUSIONS

Irrigation agriculture in Latin-American countries needs technological guidance to utilize the potential of unusual tropical conditions. Non-uniform annual distribution of rainfall combined with good soils and a 12 month growing season favor a high level of agricultural development. Supplemental irrigation, coupled with drainage of excess rainfall during wet seasons is one of the keys to successful development. Education of farmers and landowners to the acceptance of modern technology is another important key. A variety of experience from these three representative countries is available which proves that irrigation in the tropics can raise the level of agricultural production with beneficial results.

Journal of the
IRRIGATION AND DRAINAGE DIVISION
Proceedings of the American Society of Civil Engineers

DISCUSSION

[illegible]

LABORATORY RESEARCH ON INTERCEPTOR DRAINS[a]

Closure by A. R. Robinson

A. R. ROBINSON,[1] M. ASCE.—The number of discussions that were prepared on the original paper was very gratifying. To some extent these discussions indicate the need for an expanded program of research in the field of subsurface drainage. It has been the writer's experience that there is a tremendous gap between the theoretical knowledge and that which is being applied to solve field drainage problems. The study which was reported in the original paper was an attempt to bridge this gap in one selected phase of the problem.

Subsurface drainage is a phenomenon which is very complex and each situation is different in some respect from every other situation. Soil variability, both in texture and profile, is probably the most predominant factor. Many variations in hydraulic conductivity for soils of similar texture but with different structural characteristics are common. The hydraulic conductivity also may vary with moisture content. Flow in the zone of partial saturation is very complex and has not received adequate treatment. Many studies, both laboratory and field, have been made of flow below the water table, that is fully saturated. In order to reduce the number of variables, in many cases laboratory studies have been idealized to the point of questionable adaptation. The results from many field evaluations are inconclusive because numerous unmeasured variables were not considered.

The discussions have pointed out several areas in which this model study was limited or deficient. Messrs. van Schilfgaarde and Bouwer indicated the importance of flow above the water table. They point out that the amount of flow in this region of partial saturation may be appreciable. In this study the material was very coarse so that the so-called capillary fringe was approximately 1.5 in. in height. The amount of flow in this zone was undoubtedly insignificant. It is certainly true that flow in the zone of partial saturation is important in drainage considerations and has received little attention from a research standpoint.

Maasland, Sutton, Donnan, Nelson, and Long each point out the importance of the shape of water table downstream from the drain. This portion of the water table was arbitrarily fixed in the study that was reported. Nelson pointed out the relationship of the downstream condition to the upstream one. He shows that the downstream water table in the model study was always set to a smaller depth than it should have been. As a result, the upstream water table would

[a] September, 1959, by Jack Keller and A. R. Robinson. A contribution from the Soil and Water Conservation Research Div., Agric. Research Service, U. S. Dept. of Agric., and Colorado Agric. Experiment Sta., Fort Collins, Colo.

[1] Agric. Engr., Western Soil and Water Mgt. Research Branch, U. S. Dept. of Agric., Agric. Research Service, Soil and Water Conservation Research Div., and Colorado Agric. Experiment Sta., Fort Collins, Colo.

be lowered from that which was observed. This condition would also cause the drain to intercept less of the flow than would have otherwise been removed under the natural condition. Possibly the most pressing need for further drainage research is in the area downslope from the interceptor drain.

It was pointed out by Maasland and Long that the problem has been simplified to the steady state one. According to Massland, solution of steady state flow problems is inadequate for most practical problems. It is the author's observation that the steady state solution is usually the only one used for practical problems. As a general rule, the solution for the transient state becomes so involved that it is rarely ever used for the field situation. This is unfortunate since the steady state assumption is one which rarely exists. Long states that the common situation is one where there is local accretion, usually from irrigation, as well as flow from an outside source. He states that it was unfortunate that the effect of this local accretion was not evaluated in the reported study. It is certainly true that this effect should have been evaluated although the model study was not intended as a general study of drainage but was to include only one selected phase. Maasland states that an exact equation can be obtained for the water table which includes the effect of both the sloping impervious layer and surface applied recharge. Maasland implies that this solution is not yet available but can be easily obtained.

Mr. Maasland seemed to be highly disturbed that a considerable amount of information, from which he quotes, was not used for background material for the study. He also states that neither the basic differential equation nor the formula reported by Donnan (1) and used in this paper as Eq. 10 were new or of recent date. It is recognized by those trained in the field of flow in porous media that the developments of Boussinesq and Forchheimer were made. The so-called Glover formula (Eq. 10) was derived independently by Glover from heat flow analogies and is being used for interceptor drain design. It should be re-emphasized that the reported study was not meant to be a general thesis on the entire field of interceptor drainage but was only intended to encompass certain portions of the problem. Mr. Maasland was correct in pointing out that the reported hydraulic conductivity of the material seemed very low. This conductivity should have been given as 0.038 ft per sec.

Mr. Donnan points out some of the developments that led to initiation of the study. The recognition of need for the study as well as some of the preliminary planning was made by Mr. Donnan. He points out that there should be more emphasis on drainage research conducted in large tilting flumes. The author agrees that there are many phases which can be studied in a large tank. The large model gives a scaled physical picture of the problem which makes the information obtained more understandable. However, as pointed out by Bouwer, an electrical analog is especially adapted for studies of this type. Data can be collected, using an analog, at much less expense and in a shorter time. The accuracy of the data should be as good or better than when using the large equipment. As stated by Mr. Bouwer, the resistance network analog affords a simultaneous solution of flow above, as well as below, the water table.

Two significant developments by van Schilfgaarde and Nelson are of note. Mr. Nelson's starts with the basic equation and gives the boundary conditions. From these equations he selects the dimensionless parameters that completely describe the flow system. This he terms inspectional analysis in contrast to dimensional analysis, which was used in the original paper. Using this procedure, the geometry of the downstream water table was included in the problem. Mr. van Schilfgaarde rearranged the original Eq. 10 into dimensionless

form, which yielded his Eq. 2. From this, he obtained Fig. 1 which is a more usable solution than that obtained from Fig. 3 in the original paper.

From the comments of Mr. van Schilfgaarde relative to the introduction of H', an explanation is needed. In the original derivation of Eq. 10 it was evidently not recognized that in certain cases the flow in the system would not be constant before and after drain installation. In the case of a system where there is an increase in flow, a term was needed that would include the original depth, H, plus some additional depth to compensate for the additional energy in the system. The sum of these two was given the term, H', so as to not confuse the original depth of flow H.

The computational aid for the solution of Eq. 11, which was prepared by Mr. Nelson is very commendable. This will allow rapid solution of the equation for either shape of the drawdown curve or flux.

Mr. van Schilfgaarde stated that the author's data substantiate the assumptions underlying their theory and that therefore one should not hesitate to use the theory freely for solution of problems within the limitations of this study. This statement is certainly true and the major limitations should be repeated. The conditions were; (1) a sloping, impermeable boundary existed at some measurable distance below the water table, (2) a defined source existed at some determined distance from the drain location, and (3) a source that was constant in elevation and able to supply additional flow as needed to satisfy the system.

PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Department of Conditions of Practice are identified by the symbols (PP). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper number are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 2270 is identified as 2270(ST9) which indicates that the paper is contained in the ninth issue of the Journal of the Structural Division during 1959.

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SEPTEMBER: 2141(CO2), 2142(CO2), 2143(CO2), 2144(HW3), 2145(HW3), 2146(HW3), 2147(HY9), 2148(HY9), 2149(HY9), 2150(HY9), 2151(IR3), 2152(ST7)[c], 2153(IR3), 2154(IR3), 2155(IR3), 2156(IR3), 2157(IR3), 2158 (IR3), 2159(IR3), 2160(IR3), 2161(SA5), 2162(SA5), 2163(ST7), 2164(ST7), 2165(SU1), 2166(SU1), 2167(WW3), 2168(WW3), 2169(WW3), 2170(WW3), 2171(WW3), 2172(WW3), 2173(WW3), 2174(WW3), 2175(WW3), 2176 (WW3), 2177(WW3), 2178(CO2)[c], 2179(IR3)[c], 2180(HW3)[c], 2181(SA5)[c], 2182(HY9)[c], 2183(SU1)[c], 2184 (WW3)[c], 2185(PP2)[c], 2186(ST7)[c], 2187(PP2), 2188(PP2).

OCTOBER: 2189(AT4), 2190(AT4), 2191(AT4), 2192(AT4), 2193(AT4), 2194(EM4), 2195(EM4), 2196(EM4), 2197(EM4), 2198(EM4), 2199(EM4), 2200(HY10), 2201(HY10), 2202(HY10), 2203(PL3), 2204(PL3), 2205 (PL3), 2206(PO5), 2207(PO5), 2208(PO5), 2209(PO5), 2210(SM5), 2211(SM5), 2212(SM5), 2213(SM5), 2214 (SM5), 2215(SM5), 2216(SM5), 2217(SM5), 2218(ST8), 2219(ST8), 2220(EM4), 2221(ST8), 2222(ST8), 2223 (ST8), 2224(HY10), 2225(HY10), 2226(PO5), 2227(PO5), 2228(PO5), 2229(ST8), 2230(EM4), 2231(EM4), 2232(AT4)[c], 2233(PL3)[c], 2234(EM4)[c], 2235(HY10)[c], 2236(SM5)[c], 2237(ST8)[c], 2238(PO5)[c], 2239(ST8), 2240 (PL3).

NOVEMBER: 2241(HY11), 2242(HY11), 2243(HY11), 2244(HY11), 2245(HY11), 2246(SA6), 2247(SA6), 2248 (SA6), 2249(SA6), 2250(SA6), 2251(SA6), 2252(SA6), 2253(SA6), 2254(SA6), 2255(SA6), 2256(ST9), 2257(ST9), 2258(ST9), 2259(ST9), 2260(HY11), 2261(ST9)[c], 2262(ST9), 2263(HY11), 2264(ST9), 2265(HY11), 2266(SA6), 2267(SA6), 2268(SA6), 2269(HY11)[c], 2270(ST9).

DECEMBER: 2271(HY12)[c], 2272(CP2), 2273(HW4), 2274(HW4), 2275(HW4), 2276(HW4), 2277(HW4), 2278 (HW4), 2279(HW4), 2280(HW4), 2281(IR4), 2282(IR4), 2283(IR4), 2284(IR4), 2285(PO6), 2286(PO6), 2287 (PO6), 2288(PO6), 2289(PO6), 2290(PO6), 2291(PO6), 2292(SM6), 2293(SM6), 2294(SM6), 2295(SM6), 2296 (SM6), 2297(WW4), 2298(WW4), 2299(WW4), 2300(WW4), 2301(WW4), 2302(WW4), 2303(WW4), 2304(HW4), 2305(ST10), 2306(CP2), 2307(CP2), 2308(ST10), 2309(CP2), 2310(HY12), 2311(HY12), 2312(PO6), 2313(PO6), 2314(ST10), 2315(HY12), 2316(HY12), 2317(HY12), 2318(WW4), 2319(SM6), 2320(SM6), 2321(ST10), 2322 (ST10), 2323(HW4)[c], 2324(CP2)[c], 2325(SM6)[c], 2326(WW4)[c], 2327(IR4)[c], 2328(PO6)[c], 2329(ST10)[c], 2330 (CP2).

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FEBRUARY: 2355(CO1), 2356(CO1), 2357(CO1), 2358(CO1), 2359(CO1), 2360(CO1), 2361(PO1), 2362(HY2), 2363(ST2), 2364(HY2), 2365(SU1), 2366(HY2), 2367(SU1), 2368(SM1), 2369(HY2), 2370(SU1), 2371(HY2), 2372(PO1), 2373(SM1), 2374(HY2), 2375(PO1), 2376(HY2), 2377(CO1)[c], 2378(SU1), 2379(SU1), 2380(SU1), 2381(HY2)[c], 2382(ST2), 2383(SU1), 2384(ST2), 2385(SU1)[c], 2386(SU1), 2387(SU1), 2388(SU1), 2389(SM1), 2390(ST2)[c], 2391(SM1)[c], 2392(PO1)[c].

MARCH: 2393(IR1), 2394(IR1), 2395(IR1), 2396(IR1), 2397(IR1), 2398(IR1), 2399(IR1), 2400(IR1), 2401(IR1), 2402(IR1), 2403(IR1), 2404(IR1), 2405(IR1), 2406(IR1), 2407(SA2), 2408(SA2), 2409(HY3), 2410(ST3), 2411 (SA2), 2412(HW1), 2413(WW1), 2414(WW1), 2415(HY3), 2416(HW1), 2417(HW3), 2418(HW1)[c], 2419(WW1)[c], 2420(WW1), 2421(WW1), 2422(WW1), 2423(WW1), 2424(SA2), 2425(SA2)[c], 2426(HY3)[c], 2427(ST3)[c].

APRIL: 2428(ST4), 2429(HY4), 2430(PO2), 2431(SM2), 2432(PO2), 2433(ST4), 2434(EM2), 2435(PO2), 2436 (ST4), 2437(ST4), 2438(HY4), 2439(EM2), 2440(EM2), 2441(ST4), 2442(SM2), 2443(HY4), 2444(ST4), 2445 (EM2), 2446(ST4), 2447(EM2), 2448(SM2), 2449(HY4), 2450(ST4), 2451(HY4), 2452(HY4), 2453(EM2), 2454 (EM2), 2455(EM2)[c], 2456(HY4)[c], 2457(PO2)[c], 2458(ST4)[c], 2459(SM2)[c].

MAY: 2460(AT1), 2461(ST5), 2462(AT1), 2463(AT1), 2464(CP1), 2465(CP1), 2466(AT1), 2467(AT1), 2468(SA3), 2469(HY5), 2470(ST5), 2471(SA3), 2472(SA3), 2473(ST5), 2474(SA3), 2475(ST5), 2476(SA3), 2477(ST5), 2478 (HY5), 2479(SA3), 2480(ST5), 2481(SA3), 2482(CO2), 2483(CO2), 2484(HY5), 2485(HY5), 2486(AT1)[c], 2487 (CP1)[c], 2488(CO2)[c], 2489(HY5)[c], 2490(SA3)[c], 2491(ST5)[c], 2492(CP1), 2493(CO2).

JUNE: 2494(IR2), 2495(IR2), 2496(ST6), 2497(EM3), 2498(EM3), 2499(EM3), 2500(EM3), 2501(SM3), 2502 (EM3), 2503(PO3), 2504(WW2), 2505(EM3), 2506(HY6), 2507(WW2), 2508(PO3), 2509(ST6), 2510(EM3), 2511 (EM3), 2512(ST6), 2513(HW2), 2514(HY6), 2515(PO3), 2516(EM3), 2517(WW2), 2518(WW2), 2519(EM3), 2520 (PO3), 2521(HY6), 2522(SM3), 2523(ST6), 2524(HY6), 2525(HY6), 2526(HY6), 2527(IR2), 2528(ST6), 2529 (HW2), 2530(IR2), 2531(HY6), 2532(EM3)[c], 2533(HW2)[c], 2534(WW2), 2535(HY6)[c], 2536(IR2)[c], 2537(PO3)[c], 2538(SM3)[c], 2539(ST6)[c], 2540(WW2)[c].

JULY: 2541(ST7), 2542(ST7), 2543(SA4), 2544(ST7), 2545(ST7), 2546(HY7), 2547(ST7), 2548(SU2), 2549(SA4), 2550(SU2), 2551(HY7), 2552(ST7), 2553(SU2), 2554(SA4), 2555(ST7), 2556(SA4), 2557(SA4), 2558(SA4), 2559(ST7), 2560(SU2)[c], 2561(SA4)[c], 2562(HY7)[c], 2563(ST7)[c].

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c. Discussion of several papers, grouped by divisions.

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PART 2

SEPTEMBER 1960 — 30
VOLUME 86
NO. IR 3
PART 2

Your attention is invited

NEWS OF THE IRRIGATION AND DRAINAGE DIVISION OF ASCE

AMERICAN SOCIETY OF CIVIL ENGINEERS
FOUNDED 1852

JOURNAL OF THE IRRIGATION AND DRAINAGE DIVISION
PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS

DIVISION ACTIVITIES

IRRIGATION AND DRAINAGE DIVISION

Proceedings of the American Society of Civil Engineers

NEWS

September, 1960

PURPOSE: (From the ASCE Official Register)

"To promote advancement in thought and practice in the field to clarify fundamental principles, to disseminate knowledge of current practice and the results obtained therefrom and to bring about closer acquaintance of those engaged in irrigation and drainage engineering. The field of work of the Irrigation and Drainage Division includes all engineering concerned with the application of water to land or the removal of water therefrom and all of the technical, economic, and social aspects of the association of engineering with these problems. In brief, it covers all phases of irrigation, drainage, and reclamation of lands."

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Kenneth Q. Volk, Vice-Chairman
7024 Melrose Avenue, Los Angeles 38, Calif.
William W. Donnan, Secretary
P. O. Box 629, Pomona, Calif.
Prof. N. A. Christensen, (Cornell University)
412 Haushaw Road, Ithaca, New York
Herbert E. Prater, (Bureau of Reclamation)
2001 S. Madison St., Denver 10, Colo.
John Rinne, Contact member from Board of Direction
25 Van Tassel Lane, Orinda, Calif.
Carl R. Wilder, Newsletter Editor
3223 S. Columbine St., Denver 10, Colo.

CALENDAR OF COMING MEETINGS

September 29-30, 1960. Nevada Water Conference, Carson City, Nevada.

October 10-14, 1960. National Convention, ASCE. Hotel Statler, Boston, Mass. No Irrigation and Drainage Division sessions.

Note.—No. 1960-30 is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 86, No. IR 3, September, 1960.

November 16-18, 1960. National Reclamation Association, Bakersfield Inn, Bakersfield, Calif.

April 10-14, 1961. National Convention, ASCE, Phoenix, Ariz. Hotel Westward Ho. The Irrigation and Drainage Division plans to sponsor five half-day sessions as part of a week-long coordinated program devoted to water resources. This will constitute the Irrigation and Drainage Division technical conference for 1961.

June 26-July 2, 1961. 7th Congress, International Committee on Large Dams, Rome, Italy.

October 16-20, 1961. National Convention, ASCE, New York. No Irrigation and Drainage Division Sessions.

February 1962. National Convention, ASCE, Houston, Texas.

May 1962. National Convention, ASCE, Omaha, Nebraska

October 15-19, 1962. National Convention, ASCE, Detroit, Michigan.

March 1963. National Convention, ASCE, Atlanta, Georgia.

October 1963. National Convention, ASCE, San Francisco, Calif.

The Irrigation and Drainage Division plans to sponsor four half-day sessions at the Houston, Omaha, Detroit and Atlanta conventions and six sessions at the San Francisco convention. A number of general topics and specific papers already have been proposed for some of these meetings; any further suggestions should be sent to Herbert Prater or Paul Berg, Chairman and Vice-Chairman, respectively, of the Committee on Session Programs.

* * *

The Executive Committee of the Division met in Reno, Nevada, June 19 and 20, with all members present, plus contact member John Rinne of the Board of Direction, and Don P. Reynolds, Assistant to the Secretary. The next meeting of the Executive Committee is tentatively scheduled for Denver, Colorado, November 4 and 5, 1960. The following were elected to take office October 1, 1960: Kenneth Q. Volk, Chairman; N. A. Christensen, Vice-Chairman; Herbert E. Prater, Session Programs Chairman; Paul H. Berg, Session Programs Vice-Chairman; William W. Donnan, Secretary.

Christensen and Prater were appointed to study a proposal that this division sponsor a conference in 1963 on the general subject of water resources, including such topics as water supply, water shortages, and the growing crisis in water resources.

Robert Thomas reported for the Committee on Ground Water. He presented for review the Committee's "Manual of Ground Water Basin Management." Early publication of this material, possibly in a special issue of the Division Journal, is anticipated. The Executive Committee extended a vote of thanks to Chairman Harvey Banks and members of his committee for the excellent job they have done in assembling the information for this manual, and encouraged the committee to continue its work, possibly with a new objective and some additional personnel.

J. R. Davis and A. J. Boles were appointed corresponding members of the task group on Consumptive Use of the Committee on Water Conservation.

The Executive Committee discussed its past attempts to nominate someone for the Society research prize. Methods previously used to select a candidate for this prize have not had the desired results. The division Committee on Research, Gerald B. Keesee, Chairman, was instructed to consider candidates for nomination in 1961, and to present its recommendation to the Executive Committee at its next meeting.

The Committee on Cooperation with Local Sections reported that it has established relations with 42 local section groups of the Society. (Ed. note: Why can't someone from those 42 local sections let the Newsletter Editor know what they are doing?)

Chairman Bliss and Contact Member Rinne reported on the April 1960 meeting of the National Division Activities Committee. Some of the subjects discussed were as follows:

The need for well planned programs.

The matter of being able to get out news letters. (In the case of our division, we sent out a news letter with each quarterly issue of the Journal.)

The need for a strengthening, budget-wise, of the technical activities of the Society.

The need for a committee to investigate the long-term objectives of the Society as a whole.

The need for more stringent rules regarding the acceptance of papers for publication.

The need for better preparation of papers so that they can be included in the Transactions.

Formation of a Committee on Droughts has been proposed. Suggested objectives and possible studies, as follows, were tentatively adopted:

Objective: To study the nature and occurrence of cyclic and prolonged droughts and to compile information on the effect of these droughts on irrigation water supply, irrigation design and irrigation practices.

Possible Studies to be made:

(a) Frequency and distribution of droughts
(b) Effect on water supplies
(c) Effect on irrigation project planning
(d) Ways and means to alleviate effects of drought cycles
(e) Droughts in semi-arid areas

(1) Implications and economics of providing for irrigation systems to be used only intermittently

This objective and possible program was tentatively adopted by the Executive Committee and the following members were proposed to staff this committee:

Howard Critchlow, Chairman
Walter Hofmann
Leonard Halpenney
Jerry Christenson
Harry Potts
Al Christensen
Philip B. Mutz
James M. Johnston

Mr. Christensen was appointed by Chairman Bliss to contact the above proposed names in an attempt to get this committee organized.

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The Irrigation and Drainage Division of the Colorado Section elected the following officers to serve during the 1960-61 Society year:

Chairman: Walter C. Ohlsen, Bureau of Reclamation
Vice-Chairman: Fred A. Houck, Engineering Consultants, Inc.
Secretary-Treasurer: Ronald K. Blatchley, Tipton & Kalmbach, Inc.

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SENATE SELECT COMMITTEE ON NATIONAL WATER RESOURCES

The committee held hearings in October and November 1959 in 17 major cities of the United States. Most of these were in the western states, but hearings also were held in Philadelphia, Detroit and Fort Smith, Ark. With completion of the public hearings the committee is now evaluating the testimony. Many federal agencies together with some private organizations and the various states are cooperating with the committee in this evaluation.

Some of the suggestions received from witnesses at most of the hearings included:

1. Increase funds and liberalization of the small watershed program.
2. Increase grants for water pollution abatement.
3. Establish federal loan program to enable cities to fully develop water supply sites.
4. Increase all phases of water resources development research.
5. Establish a natural resources council in the White House and a joint committee on natural resources in Congress.
6. Give full consideration to recreational benefits in multiple-purpose river development.
7. Give more consideration to fish and wildlife conservation in planning water resources projects.

Transcripts of the hearings and reports of federal agencies working on this problem are being published as Committee Prints, under the general heading "Water Resources Activities in the United States." Interested engineers may obtain a listing of the available publications by addressing the committee, Washington 25, D. C.

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WORLD-WIDE ABSTRACTING AND INDEXING SERVICES

The Colorado State University Research Foundation at Fort Collins, Colorado, U.S.A., recently received a grant from the National Science Foundation for the purpose of implementing and effecting a world-wide comprehensive Abstracting and Indexing Service in the field of Soil and Water. The undertaking involves a tremendous amount of work and organization, as well as the development of a cooperative effort among many agencies. The CSURF will explore all aspects to determine the area of coverage, source of materials, availability of abstractors and translators, codification, general classification as to headings and most important of all, the types of papers to be abstracted, as well as the kind of abstracts that will be most acceptable and useful.

As world population increases, the demand for more food becomes more urgent and the two most basic requirements of fertile soil and efficient use of water will inevitably receive more attention. Investigators all over the world need to know about significant contributions and discoveries by their contemporaries as soon after publication as possible. Many months, or even years, of unnecessary effort may be avoided by access to an up-to-date information service. It is hoped that the proposed abstracting service will more adequately meet the needs of investigators in this all-important field of soil and water.

The CSURF office will welcome suggestions and ideas concerning any aspect of this undertaking, including offers to serve as abstractors, section editors and/or translators. The cooperation of all agencies related to this field of information will be welcomed.

Correspondence should be addressed to:

Soil and Water Abstracting and Indexing Project
Colorado State University Research Foundation
Fort Collins, Colorado, U. S. A.

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NEW DIRECTORY IS AVAILABLE TO MEMBERS

The 1960 Directory is now available to members on request. The Directory lists the entire membership of the Society, giving the membership grade, position, and mailing address of each. In addition, there is a complete listing of the Honorary Members, past and present, and the Life Members. A useful geographical listing of the members is also included.

It goes without saying that the information contained in the Directory is of value to every member, and every member can obtain this valuable information. To receive your free copy of the Directory simply fill out the coupon below. Prompt delivery depends on prompt return of the coupon.

The Society publishes the membership Directory every other year. The next edition will be issued in 1962.

DIRECTORY 1960

ASCE members are entitled to receive, free of charge, the 1960 ASCE Directory. To obtain the directory simply clip this coupon and mail to: American Society of Civil Engineers, 33 West 39th Street, New York 18, N. Y.

Please make the mailing label legible—correct delivery depends on you.

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With this issue of the Newsletter Ye Editor gleefully lays down his troublesome ball-point pen, hoping that some Society member more talented than he will pick it up and use it with untiring diligence. By the time this appears in print the undersigned expects to be relocated in Los Angeles, California, as Conservation Engineer for the Western Region of the Portland Cement Association. His thanks are hereby extended to all who have sent him "news" items. He hopes that all members of the Division will remember to advise the new editor, Kenneth O. Kauffman, 902 East G Street, McCook, Nebraska, of newsworthy happenings in their areas of activity. It's been a pleasure to serve you. Au revoir!

Carl R. Wilder